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A LABORATORY STUDY OF ASPHALT CONCRETE MIX DESIGNS FOR HIGH-CONTACT PRESSURE AIRCRAFT TRAFFIC

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This report documents a laboratory-based research effort to study the effects of high-contact pressure F-4 and F-15 aircraft traffic in the 350-400 psi range on conventionally designed heavy-duty asphalt concretes. Specimens of mix were prepared to current heavy-duty compactive effort (75 blow per side with an impact hammer) and four other compactive efforts, using a modified gyratory compactor. The gyratory compactor was used to roughly simulate high-contact pressure traffic on some of the mixes. Two aggregate gradations recommended for high-pressure traffic were used to produce crushed limestone aggregate blends. Two grades of asphalt cement, AC 20 and AC 40, and a Chemkrete®-modified AC 20 asphalt cement were used as binders.

Heavy-duty mix selection criteria were used to bracket optimum mixes for supplemental testing and analysis. Testing consisted of indirect tensile tests (dynamic and static), direct shear tests, accelerated aging tests, and unconfined creep tests. (Continued)

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19. ABSTRACT (Continued).

Results indicated that current heavy-duty mix selection criteria can be used, but higher compactive effort is needed to prevent rutting and densification problems. Lower asphalt content mixes were selected when higher compactive efforts were used.

Two modified methods of designing high-contact pressure asphalt concrete mixes were presented. The preferred method is based on the use of a gyratory compactor at a higher compactive effort. The second method, an approximate method for use when a gyratory compactor is not available, is based on use of the current 75-blow per side impact hammer. Several mixes were recommended for use in a field test at Tyndall AFB, Florida.

PREFACE

This report was prepared by the Geotechnical Laboratory, US Army Engineer Waterways Experiment Station, Vicksburg, Mississippi 39180, under Military Interdepartmental Purchase Requests N-83-6-05, N-84-25, and N-85-2 for the Air Force Engineering and Services Center, Tyndall Air Force Base, Florida.

This report summarizes work done between October 1983 and June 1986. Captains John D. Wilson, George E. Walrond, and Martin D. Lewis were the HQ AFESC/RDCR project officers.

This report documents laboratory testing and the development of a modified mix design method for asphaltic concrete surfaces for very high contact pressures of heavyweight F-15 aircraft.

This report has been reviewed by the Public Affairs Office and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public including foreign nationals.

This technical report has been reviewed and is approved for publication.

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TABLE OF CONTENTS

TABLE OF CONTENTS
(CONCLUDED)

LIST OF FIGURES

LIST OF FIGURES
(CONTINUED)

LIST OF FIGURES
(CONCLUDED)

LIST OF TABLES

LIST OF TABLES
(CONCLUDED)

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SECTION I

INTRODUCTION

A. OBJECTIVES

The objectives of this study were to investigate the effects of heavy-weight F-15 aircraft traffic with 350-400 psi contact pressures on properties of conventionally designed airfield asphalt concrete surface mixes and to develop a modified mix design procedure to optimize the behavior of mixes subjected to these nontypical types of traffic.

B. BACKGROUND

Increased or expanded use of aircraft such as the F-4 or F-15 will lead to increased aircraft gear loads and increased tire contact pressures that must be resisted by an airfield pavement. Anticipated aircraft pressures up to 400 psi must be resisted by the pavement surface and efficiently transferred to lower pavement layers in a manner that will provide maximum pavement life and good performance.

Asphalt concrete hot mix, designed with the aid of the Marshall Method, has provided satisfactory surfaces for airfield runways for many years. However, in the past, tire contact pressures have not generally exceeded 250 psi. As a result, current mix design methods for surface mixes may be limited by their empirical nature. Thus, there is a need for an evaluation of current empirical methods of mix design, and consideration should be given to modifications based on more fundamental engineering characteristics.

Fundamental mix properties based on weight-volume relationships, an understanding of compaction behavior, and the use of supplemental testing, based on theoretically founded analysis, should provide a sound engineering basis for selecting an adequate surface course mix. Current practice includes the use of Marshall stability and flow measurements, along with voids total mix, voids filled with asphalt, and total unit weight, to select a design mix. Use of current heavy-duty design criteria in conjunction with present standard compactive efforts in designing mixes to support very-high-contact pressures, outside current experience, may not provide sound, strong, and durable surfaces.

1. General Design of Asphalt Mixtures

The overall design process for asphalt pavement layers is basically a compromise to optimize several basic mix characteristics. Reference 1 and Table 1 summarize some of the mix properties and the desirable control properties. General properties of interest include stability, tensile strength, durability, fatigue resistance, permeability or imperviousness, skid resistance, and flexibility.

a. Stability is commonly defined as resistance to deformation under load. This includes nonrecoverable deformations from both vertical rutting and plastic movement in the longitudinal and lateral directions. Typically,

TABLE 1. CHARACTERISTICS TO OPTIMIZE MIXTURE PROPERTIES (FROM REFERENCE 1).

Desirable mix property	Levels of mix variables: Bitumen content	Aggregate gradation	Degree of compaction
Stability	Low	Dense	High
Durability	High	Dense	High
Flexibility	High	Open	----
Fatigue resistance	High	Dense[a]	High[b]
Skid resistance	Low	Dense or open[c]	High
Imperviousness	High	Dense	High
Tensile strength	High	Dense	High

[a]Assuming a heavy-duty, comparatively thick layer of bituminous concrete.

[b]Although compaction is not normally indicated for this property, it is implied to ensure that aggregate particles will not dislodge.

[c]Both types of gradations have good skid-resistance characteristics. What appears to be more important is the texture of the aggregate particles.

stiffness of the asphalt cement dominates the stability behavior at low temperatures and frictional resistance of the mix dominates at higher temperatures.

b. Tensile strength is the maximum strength the mix can develop when subjected to tensile forces. High tensile strength is most important at low temperatures or in situations where underlying pavement layers can change volume and generate tensile forces in the surface layer.

c. Durability can be defined as a resistance to wear and weathering. Wear includes abrasive traffic action on the aggregate and the asphalt. Weathering includes changes to the asphalt cement from volatile losses and oxidation and the effects of water action on the mix.

d. Fatigue resistance, which is the ability of a paving mixture to withstand repeated loadings, has been studied by many pavement researchers. It is not considered to be of primary interest in this study because of the anticipated relatively low volumes of traffic for fighter aircraft. Although fatigue resistance is secondary to pavement stability, it will affect mix performance at very high traffic volumes.

e. Permeability of a dense asphalt concrete mix is intended to be low because it is designed to perform a waterproofing function. For low permeability, a mix should have similar properties to those necessary for good durability. Conversely, high mixture permeability is sometimes desirable to provide good skid resistance during wet weather. Porous friction surfaces are examples of highly permeable pavement mixes.

f. Skid resistance is generally ensured by providing those things necessary for stability behavior. These necessities include the use of hard, wear-resistant, crushed aggregates and relatively low asphalt contents to provide sharp surface points of contact.

g. Flexibility is the ability of the surface course mixture to conform to long-term changes or movements in underlying components. These changes can be a result of settlement, shear, or differential traffic-induced compaction of deeper layers.

All the preceding mix properties depend on certain key mix variables. As indicated in Table 1, these are asphalt content, aggregate gradation, and degree of compaction.

2. Aggregate Gradations and Blends

Aggregate gradations for asphalt concrete mixes are generally blends of two or more stockpiled aggregates. Mostly crushed, well-graded aggregate blends are required for airfield surface mixes.

Technical Manual (TM) 5-822-8/AFM 88-6, Chapters 2 and 9 (Reference 2), contains recommended gradations for asphalt mix to be subjected to low and high tire pressure. Low-pressure applications include those for ordinary traffic with contact pressures up to 100 psi. When pressures exceed 100 psi (as with aircraft, tracked vehicles, or vehicles with solid tires), the high tire pressure gradations are recommended. Choice of maximum aggregate size is a function of final layer thickness, availability of aggregates, and other considerations. As a general rule, the maximum aggregate size should not exceed one-half of the compacted layer thickness.

These recommended gradations are also based on limited amounts of material passing the Number 200 screen (-200 material). For all high pressure applications, the range of -200 material is limited to 3-6 percent by weight. The purpose of this limitation is to ensure that a stable, durable mixture is obtained. High amounts of -200 material result in the mixture having a lower asphalt content leading to higher stability and lower durability. Low amounts of -200 material result in the mixture having a higher asphalt content leading to lower stability and higher durability. Thus, the amount of -200 material must be controlled to ensure satisfactory stability and durability.

Current Asphalt Mix Guide Specification (CEGS-02556) (Reference 3) limits the total amount of natural sand to 15 percent by total weight in mixes for heavy-duty applications. The natural sand particles are assumed to be rounded. Since strength and aggregate interlock are necessary in surface mixes, this limitation on rounded sand helps maintain a high degree of physical stability to the aggregate matrix.

3. General Compaction Requirements for Pavement Mixtures

The term "compaction" can be defined in very general terms as the process of applying energy to a mass to decrease its volume. In paving mixtures, especially asphalt concrete surfaces, compaction is required to provide adequate shear strength, prevent further significant densification under traffic, prevent excessive hardening of the asphalt cement due to oxidation, and provide an essentially waterproof layer to protect underlying pavement layers (Reference 4).

4. Specific Design of Surface Mixtures

A surface mix is designed to perform the preceding general functions and to meet specific design criteria, based on anticipated service requirements. Essential steps in the design process are:

a. Selection of the proper aggregate gradation.

b. Laboratory production and compaction of several mixes at an adequate compactive effort, resulting in a density equal to that which will be obtained in the field under traffic. Mixes are prepared and compacted to study the general behavior of mixes as a function of asphalt content.

c. Analysis of compacted mix properties.

d. Supplemental testing of mixes as required to satisfy specific design criteria. With the Marshall Method of design, these tests include Marshall stability and flow measurement at 140 °F for mixes made with asphalt cements.

e. Utilization of results from Steps b-d to select an optimum asphalt content and design density.

C. SCOPE

The scope of this study was limited to laboratory mix production, testing, and analysis of the generated data. Conventional Marshall procedures and empirical mix design criteria were summarized and examined in the investigation. Nonconventional test background and procedures were also summarized and used to develop data on several mixes. Indirect tensile tests (static and dynamic), accelerated aging tests, direct shear, and unconfined creep tests were performed on mixes produced at five compactive efforts, including the 75 blow per side effort for high tire pressure and four levels of gyratory compaction, with two aggregate gradations and three types of asphalt cement.

1. Materials

This investigation was conducted using all crushed limestone aggregate, an AC 20 grade asphalt cement supplied by Tyndall Air Force Base (AFB), Florida, AC 40 asphalt cement from the US Army Engineer Waterways Experiment Station (WES) stock, and a Chemkrete®-modified AC 20 asphalt cement.

a. Aggregate Gradation

Aggregate was separated by sieve sizes and blended to obtain two gradations recommended for heavy-duty high-pressure applications (Reference 2). Table 2 and Figure 1 show the gradations used. One was a 3/4-inch

TABLE 2. AGGREGATE GRADATIONS AND SPECIFIC GRAVITY.

US standard sieve size	Specifications[a] 3/4-Inch range	Specifications[a] 1-Inch range	Gradations used 3/4-Inch	Gradations used 1-Inch
1 inch	100	100	100	100
3/4 inch	100	84-96	100	84
1/2 inch	82-96	74-88	90	75
3/8 inch	77-89	68-82	84	68
No. 4	59-73	53-67	67	54
No. 8	46-60	40-54	54	40
No. 16	34-48	30-44	43	30
No. 30	24-38	20-34	31	21
No. 50	15-27	13-25	22	16
No. 100	8-18	9-17	12	9
No. 200	3-6	3-6	6	6

[a]From TM 5-822-8/AFM 88-6, Chapters 2 and 9 for high-pressure applications (Reference 2).

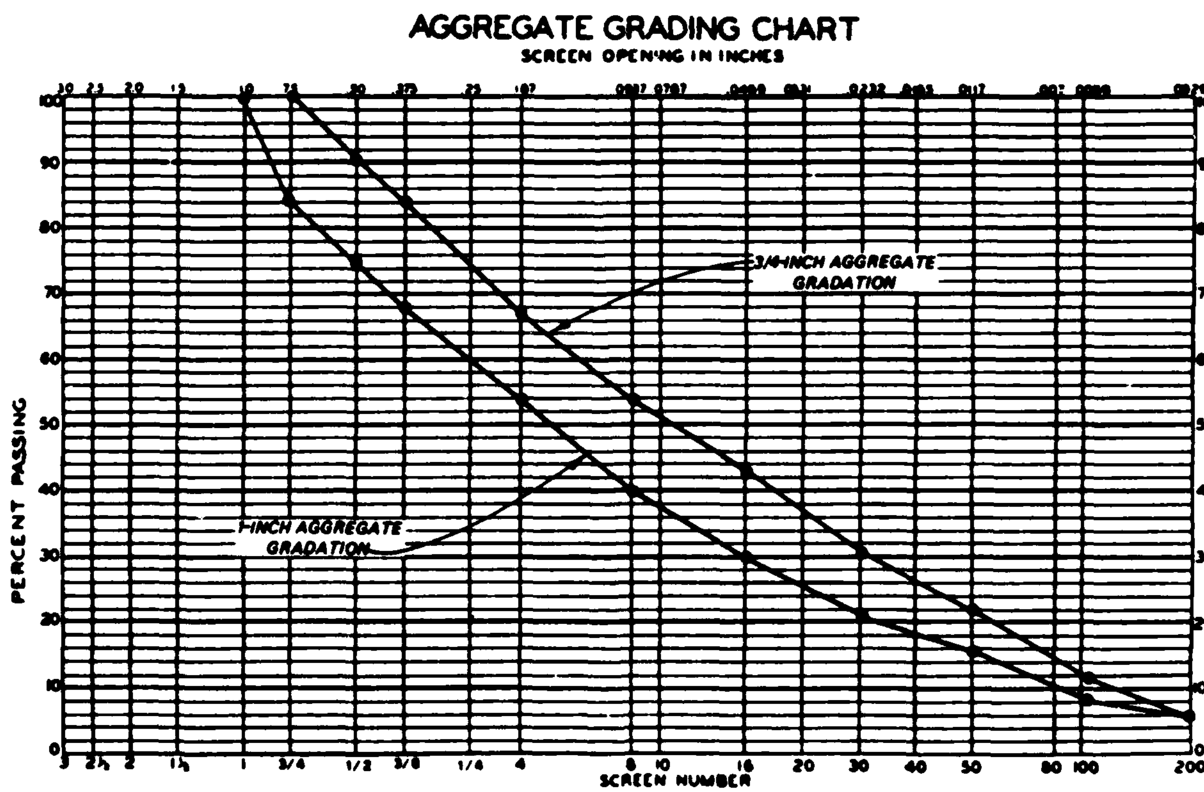

Figure 1. Limestone Aggregate Gradations.

maximum size gradation representing the middle of the 3/4-inch band for airfields; the other was a 1-inch maximum size gradation representing the coarse extreme of the 1-inch band.

b. Asphalt Cement and Modifier

Table 3 provides a summary of asphalt properties. The AC 40 was included in the study to provide relative comparisons of the effects of viscous and less viscous asphalt cement on mix behavior. To produce mixes with Chemkrete®, a commercial proprietary asphalt modifier was mixed with AC 20 asphalt cement in a series of tests to observe the effect of this modifier on

TABLE 3. PROPERTIES OF ASPHALT CEMENTS.

Property	ASTM Method	AC 20	AC 40
Penetration - 77 °F (25 °C), 100g, 5 sec, 0.1 mm	D 5	75	56
Specific gravity - 77 °F (25 °C)	D 70	1.032	1.040
Ductility - 77 °F (25 °C), cm	D 113	150+	150+
Viscosity			
140 °F (60 °C), poises	D 2171	2,102	4,506
225 °F (107 °C), centistokes	D 2170	2,170	3,908
275 °F (135 °C), centistokes	D 2170	423	704
Flash point, °F	D 92	575	---
Solubility, percent	D 2042	99.55	---
Thin film oven loss, percent	D 1754	0.434	0.147
Residual penetration 77 °F (25 °C), 100 g, 5 sec, 0.1 mm	D 5	52	38
Viscosity - 140 °F (60 °C), poises	D 2171	---	11,348
225 °F (107 °C), centistokes	D 2170	3,505	6,553
275 °F (135 °C), centistokes	D 2170	558	1,018
Ductility - 77 °F (25 °C), cm	D 113	---	119

mix behavior. Table 4 summarizes properties of Chemkrete®, as given in the manufacturer's literature.

2. Test Plan

Asphalt mixtures made with the previously discussed materials were tested according to a test plan that was divided into three phases:

a. Phase 1 - Preliminary Mix Properties and Test Results

Impact and gyratory compaction methods were used to produce several levels of effort on mixes made with the three asphalt cements and both

TABLE 4. CHEMKRETE® ASPHALT MODIFIER[a] DATA (1984 MANUFACTURER'S LITERATURE).

Property	Typical value
Physical	
Specific gravity, 60 °F	0.97
Viscosity, centistokes	
104 °F	40
212 °F	7
275 °F	4
Flash point	
Pensky-Martens closed cup, °F	356
Pour point, °F	22
Chemical[a]	
Manganese, percent weight	2.0-2.5

[a]An oil-based soap containing manganese in liquid form.

aggregate gradations. Typical mix data were developed by compaction at five efforts--four gyratory compactive efforts and one impact hammer effort (75 blow per side). Asphalt contents were increased in 0.50-percent increments and the average of three specimens was used for each data point or property.

b. Phase 2 - Selection of Optimum Asphalt Contents and Production of Specimens for Nonconventional Testing

Optimum asphalt contents were chosen based on current mix design criteria for high-pressure mixes. Nonconventional tests were planned for mixes with asphalt contents in the vicinity of selected optimums. Asphalt contents selected were chosen to bracket optimums by 0.50 percent (optimum ±0.50 percent). Mixes were made using the five previous compactive efforts.

c. Phase 3 - Nonconventional Testing

Basic nonconventional testing included indirect tensile tests (static and dynamic), direct shear tests, unconfined creep tests, and accelerated aging tests on 4-inch diameter by 2-1/2-inch-high disc-shaped specimens of mix.

The overall plan was to analyze results from the three phases and recommend mix design requirements for asphalt surface mixes to resist 350-400 psi contact pressure traffic. Mixes that appear adequate will be evaluated in a full-load, accelerated-traffic test area by the Air Force Engineering and Services Laboratory, Tyndall AFB, Florida.

SECTION II

COMPACTION OF PAVING MIXTURES

Asphalt mixtures must be compacted to produce the properties necessary for good pavement service life. A pavement is initially compacted during construction. However, additional densification can occur because of traffic. For military airfields, the current standard for heavy-duty asphalt pavements requires a minimum field compactive effort of 98-100 percent of the laboratory density obtained using 75 blows per side.

A. LABORATORY COMPACTION METHODS

Current methods of asphalt concrete paving mix design are based on the use of mold-confined laboratory-compacted specimens. Generally, disc, cylindrical, or beam specimens are produced. Three common methods of laboratory compaction include impact compaction, gyratory compaction, and kneading compaction.

1. Impact Compaction

Impact compaction is done with a 10-pound sliding hammer raised and dropped 18 inches onto a baseplate, slightly smaller than the 4-inch inside diameter of a 3.4-inch-high Marshall compaction mold. The weight is either manually or mechanically moved to compact an asphalt mix inside the mold. Both faces or sides of the asphalt mix are compacted. Hammer impacts force the mix into a denser state. Disc-shaped specimens with 4-inch diameters and approximate 2-1/2-inch heights are generally produced with this method. A summary of development of this method can be found in References 5 and 6.

2. Gyratory Compaction

Gyratory compaction methods usually apply normal forces to both top and bottom faces of the asphalt mix confined in cylindrical-shaped molds. Normal forces are supplemented with a rocking or gyrating motion to work the mix into a denser configuration while totally confined. The Texas Highway Department (Reference 7) and the US Army Corps of Engineers (References 8-10) have developed methods, procedures, and equipment using this compaction method. The inside diameter of the molds are either 4 or 6 inches; compacted specimens can be either cylindrical or disc-shaped.

3. Kneading Compaction

Kneading compaction methods generally apply forces to a portion of a free face of an otherwise confined asphalt mix. Compactive forces are applied uniformly around the free face. The partial free face allows particles to move relative to each other, creating a kneading action that densifies the mix. This method was devised by the State of California Materials and Research Laboratory.

B. GENERAL COMPACTION BEHAVIOR OF PAVING MIXTURES

Compaction behavior of geotechnical materials is generally expressed in a density-fluid content curve. When working with paving mixtures, a density-asphalt content plot is generated. Individual densities can either be shown in terms of total mixture or aggregate only unit weight. The relationship between the two densities is:

$$\gamma_{ag} = \gamma_m(100 - AC)/100 \tag{1}$$

where

γ_{ag} = aggregate density, pcf

γ_m = total mix density, pcf

AC = asphalt content in percent (i.e. 4 percent = 4.0), defined as weight of mix.

For a given compactive effort, compaction behavior across a range of asphalt contents can be analyzed with the aid of a generalized cubic or third-order regression model

$$\gamma_{ag} = a_o + a_1(AC) + a_2(AC)^2 + a_3(AC)^3 \tag{2}$$

where a_o, a_1, a_2, a_3 are regression constants.

Differentiating Equation (2) and setting it equal to zero allows the determination of asphalt contents where aggregate density is either a maximum or minimum value; the following equation allows determination of those asphalt contents.

$$AC = \frac{-a_2 \pm \sqrt{a_2^2 - 3a_3a_1}}{3a_3} \tag{3}$$

Two solutions are found from this equation; each represents one of three possible conditions: (1) An asphalt content at a relative minimum aggregate density, (2) An asphalt content at a relative maximum aggregate density, or (3) An asphalt content that is higher or richer than that required for maximum aggregate density. An overly rich asphalt content may be computed if initial compaction data is more representative of a parabolic or second-order compaction curve.

Similarly, the volume of voids in the mineral aggregate (VMA) (same as porosity in soil terminology) is also an indicator of relative maximum and minimum aggregate density. From the fundamental relationships of Table 5, the volume of voids in the aggregate matrix, as a decimal fraction of total volume, is

$$VMA = 1 - \frac{\gamma_{ag}}{G_s\gamma_w} \tag{4}$$

TABLE 5. WEIGHT-VOLUME RELATIONSHIPS IN TERMS OF MIX AND AGGREGATE DENSITIES.

Property	Mix	Aggregate
Asphalt content, AC (percent total volume)	$\frac{\gamma_m(AC)}{\gamma_w G_b} \times 100$	$\frac{\gamma_{ag}(AC)}{\gamma_w G_b(1 - AC)} \times 100$
Voids in mineral aggregate, VMA (percent total volume)	$\left[1 - \frac{\gamma_m(1 - AC)}{\gamma_w G_s}\right] \times 100$	$\left(1 - \frac{\gamma_{ag}}{\gamma_w G_s}\right) \times 100$
Air voids (percent total volume)	$\left\{1 - \frac{\gamma_m}{\gamma_w}\left[\frac{AC}{G_b} + \frac{(1 - AC)}{G_s}\right]\right\} \times 100$	$\left\{1 - \frac{\gamma_{ag}}{\gamma_w(1 - AC)}\left[\frac{AC}{G_b} + \frac{(1 - AC)}{G_s}\right]\right\} \times 100$
Voids filled with asphalt (percent total voids)	$\frac{\gamma_m G_s(AC)}{G_b\left[\gamma_w G_s - \gamma_m(1 - AC)\right]} \times 100$	$\frac{\gamma_{ag} G_s(AC)}{(1 - AC)G_b(\gamma_w G_s - \gamma_{ag})} \times 100$
Zero air voids curve	$\gamma'_m = \frac{\gamma_w G_s G_b}{G_s(AC) + G_b(1 - AC)}$	$\gamma'_{ag} = \frac{\gamma_w G_s G_b(1 - AC)}{G_s(AC) + G_b(1 - AC)}$

where

γ_m = unit weight of total mix

AC = asphalt content based on total mix weight (expressed as a decimal)

γ_w = unit weight of water

G_b = specific gravity of asphalt cement

γ_{ag} = unit weight of aggregate

γ'_m = theoretical maximum unit weight of mix

G_s = apparent specific gravity of aggregate

γ'_{ag} = theoretical maximum unit weight of aggregate

Differentiating with respect to asphalt content gives

$$\frac{d(VMA)}{d(AC)} = -\frac{1}{G_s \gamma_w} \left[\frac{d(\gamma_{ag})}{d(AC)}\right] \qquad (5)$$

Figure 2 and Equation (5) show that, as AC increases, the volume of pores in the mix decreases on the lean side of maximum aggregate density. At maximum aggregate density, there is no change in the volume of total voids for an incremental change in asphalt content. As the asphalt content increases beyond the point of maximum density, asphalt begins to interfere with compaction of the aggregate particles. Asphalt displaces aggregate particles and causes the volume of voids in the aggregate matrix to increase on the rich side of the aggregate density curve.

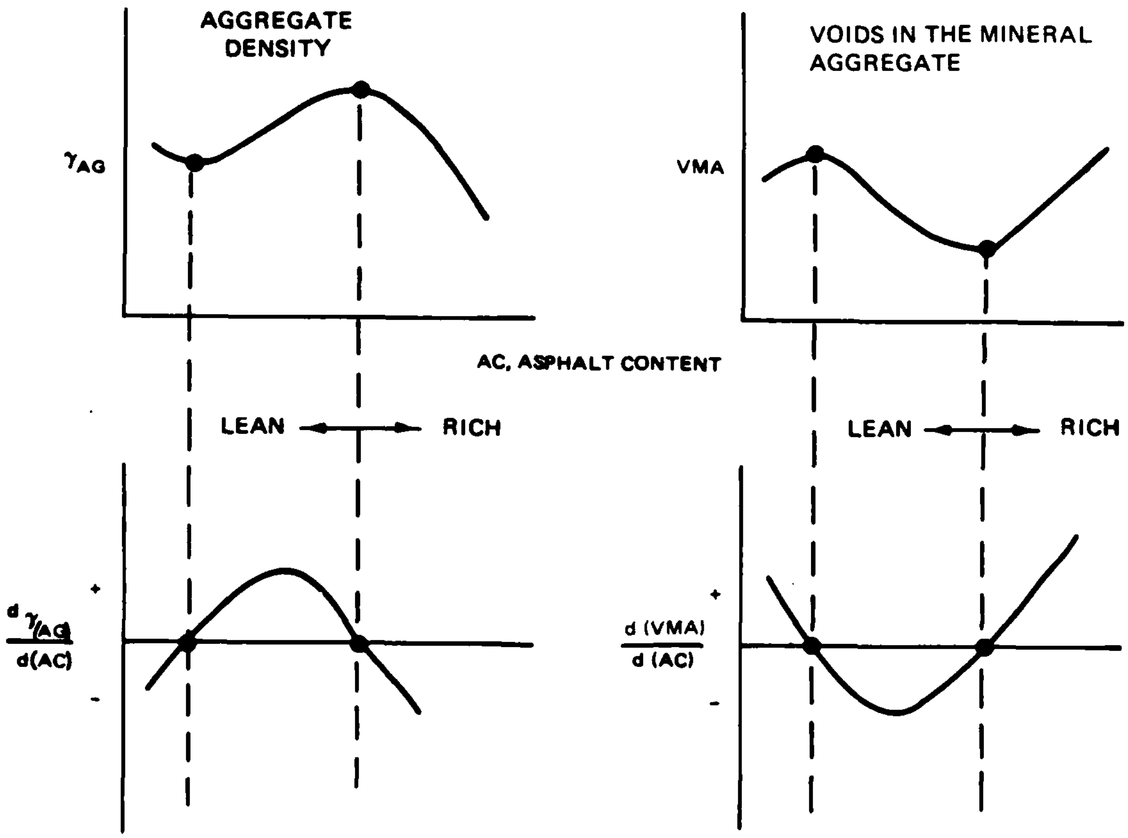

Figure 2. General Compaction Behavior of Paving Mixtures.

SECTION III

MIX DESIGN METHODS, CRITERIA, AND ANALYSIS

A. MARSHALL MIX DESIGN METHOD

Currently, within the Department of Defense, the Marshall Method is used to design asphalt concrete hot mixes for aircraft usage. Bruce Marshall of the Mississippi State Highway Department developed a procedure during the 1930s that was later modified by the Corps of Engineers into its present form. Modifications or changes to the original procedure were made based on performance under aircraft traffic conditions. The Marshall Method is empirical and based on past experience. Guidance on the method is given in TM 5-822-8/AFM 88-6 Chapters 2 and 9, and Military Standard 620A (References 2 and 11).

1. Impact Hand Hammer

Two levels of laboratory compactive effort are used with an impact hand hammer. Both are based on the 10-pound manually operated hammer (impact compaction) with an 18-inch fall. The first level of effort is used in designing mixtures for traffic with low-pressure tires such as streets and parking areas subject to traffic contact pressures up to 100 psi. It consists of 50 blows on each face of a representative sample of asphalt concrete mix. The second level of effort uses 75 blows on each face of a sample, and is used for designing asphalt mixes where contact pressures exceed 100 psi, up to a maximum of about 250 psi. Aircraft pavements are typically designed with the 75 blow per side compactive effort.

2. Gyratory Compactor

A second method of laboratory compaction that can be used for Marshall mix design is gyratory compaction. Equipment and procedures were developed at WES. With this procedure, an asphalt mix is placed in a steel mold, put into the gyratory compactor, loaded to a preselected normal pressure which represents the anticipated contact pressure and gyrated through an angle of 1 degree for a number of revolutions of the roller assembly (Figure 3). Military Standard 620A (Reference 11) has suggested equivalency of the following types of compaction and compactive efforts.

Gyratory Compaction	Impact Compaction
100 psi, 1-degree angle, 30 revolutions	50 blow per side
200 psi, 1-degree angle, 30 revolutions	75 blow per side

After specimens have been compacted at various asphalt contents, fundamental average weight-volume properties are determined for each asphalt content. Properties include density, air voids in the mix, voids filled with asphalt, and sometimes voids in the mineral aggregate. Specimens made with asphalt cements are heated to 140 °F in a water bath before performing Marshall stability and flow testing with a Marshall compression machine. Maximum load is recorded as the Marshall stability, and the amount of specimen deformation, in hundredths of an inch, is recorded as the flow.

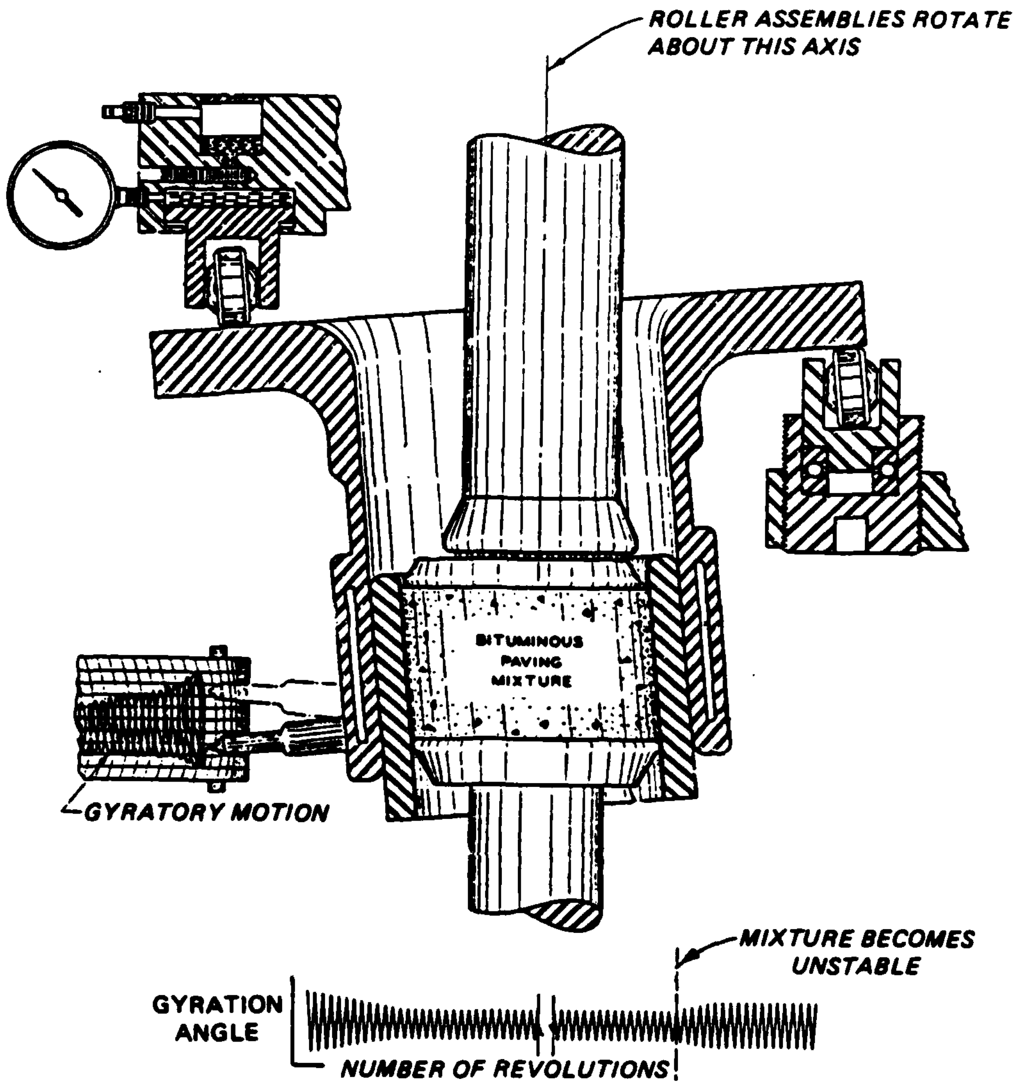

Figure 3. Schematic of the Gyratory Compactor.

Criteria used to determine optimum or design asphalt contents for mixes made with either compaction method are summarized in Tables 6 and 7.

B. GYRATORY MIX DESIGN METHOD

The gyratory method of mix design is documented in Method 102 of Military Standard 620A (Reference 11) and ASTM Method D3387 (Reference 12). This method's procedure is simple and does not require many computations to determine a design asphalt content; it is based on indicated mix stability as shown by the gyrograph trace of mix behavior during compaction.

The mix is placed into a mold, a confining pressure equivalent to that expected by traffic is applied to the mix, and it is compacted by rotating the

TABLE 6. DESIGN CRITERIA FOR USE WITH ASTM APPARENT SPECIFIC GRAVITY[a]

A. PROCEDURE FOR DETERMINING OPTIMUM BITUMEN CONTENT

Test property	Points on curve: 50 Blows normal-duty	Points on curve: 75 Blows heavy-duty
Marshall stability	Peak of curve	Peak of curve
Total unit weight	Peak of curve	Peak of curve
Flow	Not used	Not used
Percent voids total mix	4	4
Percent voids filled with bitumen	80	75

B. PROCEDURE FOR DETERMINING SATISFACTORINESS OF MIX

Test property	Criteria: 50 Blows normal-duty	Criteria: 75 Blows heavy-duty
Marshall stability	500 lb or higher	1,800 lb or higher
Total unit weight	Not used	Not used
Flow	20 or less	16 or less
Percent voids total mix	3-5	3-5
Percent voids filled with bitumen	75-85	70-80

[a]For use with aggregate blends showing water absorption up to 2.5 percent.

TABLE 7. DESIGN CRITERIA FOR USE WITH BULK-IMPREGNATED SPECIFIC GRAVITY.[a]

A. PROCEDURE FOR DETERMINING OPTIMUM BITUMEN CONTENT

	Points on curve	
Test property	50 Blows normal-duty	75 Blows heavy-duty
Marshall stability	Peak of curve	Peak of curve
Total unit weight	Peak of curve	Peak of curve
Flow	Not used	Not used
Percent voids total mix	3	3
Percent voids filled with bitumen	85	80

B. PROCEDURE FOR DETERMINING SATISFACTORINESS OF MIX

	Criteria	
Test property	50 Blows normal-duty	75 Blows heavy-duty
Marshall stability	500 lb or higher	1,800 lb or higher
Total unit weight	Not used	Not used
Flow	20 or less	16 or less
Percent voids total mix	2-4	2-4
Percent voids filled with bitumen	80-90	75-85

[a]For use with aggregate blends showing water absorption greater than 2.5 percent.

roller assembly through 30 revolutions. As the mix is compacted, a gyration graph is generated by the compactor. This graph is used to indicate the relative stability behavior of the mix during compaction.

When the gyrograph spreads or widens during mix compaction, the mix is indicated as unstable (Figure 4). However, if it does not spread, the mix is indicated as stable under given conditions of compaction. The gyrograph shows the response of the mix to the compactive effort induced by the compactor. From the gyrograph trace, the ratio of final width to intermediate width is called the gyratory stability index (GSI). Most mixes show this unstable behavior or widening of the gyrograph on the rich or more saturated side of the aggregate density-asphalt content curve. The amount of asphalt in the mixture is so high that all applied external forces are resisted by the asphalt, causing plastic deformation of the sample.

The design asphalt content is simply the maximum asphalt content where the mix has a GSI value of 1.0 (stable behavior). Design density is also given by the stable mix with the highest asphalt content.

C. GYRATORY COMPACTION: ANALYSIS OF TRAFFIC-INDUCED DENSIFICATION

Two studies (References 13 and 14) and many WES analyses of airfield asphalt concrete performance have indicated that 200 psi gyratory compaction can reasonably approximate mix densification under traffic. However, these studies were based on aircraft traffic that seldom exceeded 250 psi contact pressures and used mixes that were designed and constructed to 75 blow per side or high-pressure tire mix design.

An early study of the effects of B-52 aircraft traffic on surface coarse mixes used the WES-developed gyratory compactor to help analyze traffic-induced densification (Reference 13). Surface mixes were designed and constructed using 75 blow per side compactive efforts. Full-load, full-scale traffic was applied to several test areas at contact pressures ranging from 220-290 psi. The comparison of before- and after-traffic density data showed that traffic had further densified the mixes. Data also indicated that gyratory compaction at 200 and 300 psi normal pressures produced mix densities that were close to after-traffic densities in the traffic areas.

A later study of in-service pavements examined the effects of T-38 aircraft traffic on asphalt concretes (Reference 14). Core samples of pavement were removed from 23 taxiways at several Air Force bases where T-38 training aircraft, with 240 psi contact pressures, provided most of the traffic. Gyratory recompactions of core samples were found to produce densities similar to those of the traffic-densified mixes. The recompactions were performed on samples that had been heated to approximately 250 °F and then compacted in a gyratory compactor set at 200 psi normal pressure, 1-degree gyration angle, and 30 revolutions of the machine.

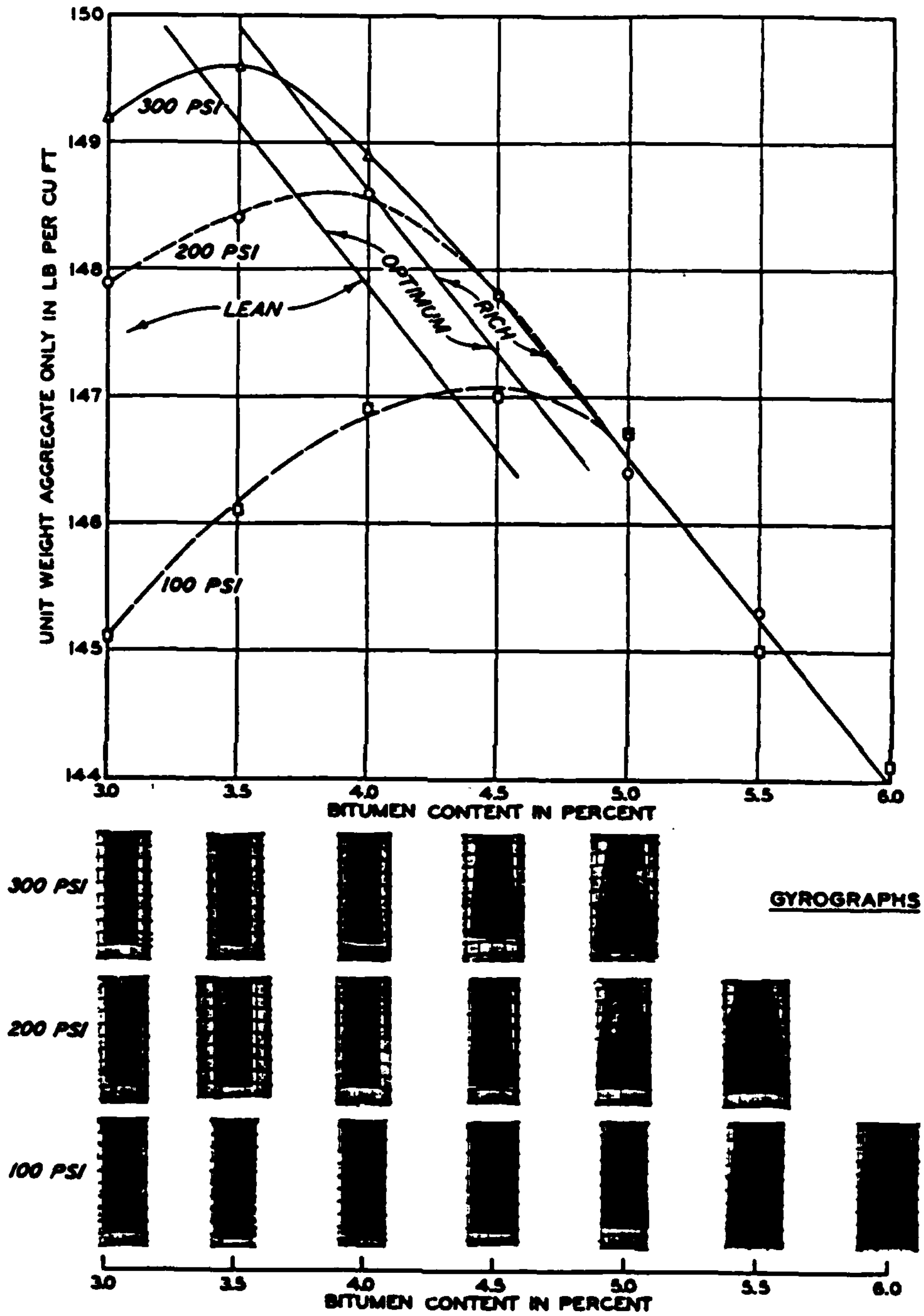

Figure 4. Gyrographs and Effects of Increased Compactive Effort with the Gyratory Compactor.

SECTION IV

SUPPLEMENTAL TESTS: BACKGROUND, THEORY, AND EQUATIONS

The stability and flow tests used with the Marshall Mix Design Method are empirical. Recently, tests have been developed and are being used by engineers to determine more fundamental properties of geotechnical construction materials and pavement mixes. Several tests were considered for this study; however, the list was reduced to the following as fundamental indicators of mix elasticity, strength, durability, and rutting potential:

- Indirect Tensile Test.
- Direct Shear Test.
- Accelerated Aging Test.
- Creep Test.

A. INDIRECT TENSILE TEST

The indirect tensile test is a tool used by geotechnical and structural engineers to compute fundamental properties of materials. Reference 15 provides a comprehensive general summary of the test. References 16-19 provide specific equations for application of the test to asphalt concrete mixes and materials. ASTM methods C 496 and D 4123 provide guidance on testing concrete and bituminous mixes, respectively (Reference 12).

In 1953, a procedure for indirectly determining tensile strengths of materials was developed simultaneously in both Brazil and Japan (Reference 15). A cylinder of material is placed horizontally between two plane-loading surfaces; load is applied to the specimen across its diameter until the material splits or fails in tension. Since its development, this procedure has been used to test concrete, soils, cement-stabilized materials, and asphalt concrete materials. Figure 5 illustrates the basic test arrangement.

1. Theory of the Indirect Tensile Test

Mathematical analyses of stresses and strains within a circular disc of material, loaded across its diameter, have been studied by many people. In 1883, Hertz first examined the problem; Frocht, Timoshenko and Goodier, Muskhelishvilli, and Hondros also contributed to the analysis (Reference 17).

Hondros's contribution has been used since the 1960s to analyze cement-stabilized materials and asphalt concretes (References 16 and 17). His work showed that both plane stress and plane-strain conditions can be given by one set of equations for stresses across vertical and horizontal diameters of a specimen with a circular cross section. Compressive loads are applied to the specimen in the vertical direction along a diameter. The center of the specimen, intersecting vertical and horizontal diameters, is the origin of the coordinate system. From Reference 18, Hondros's equations were summarized as follows.

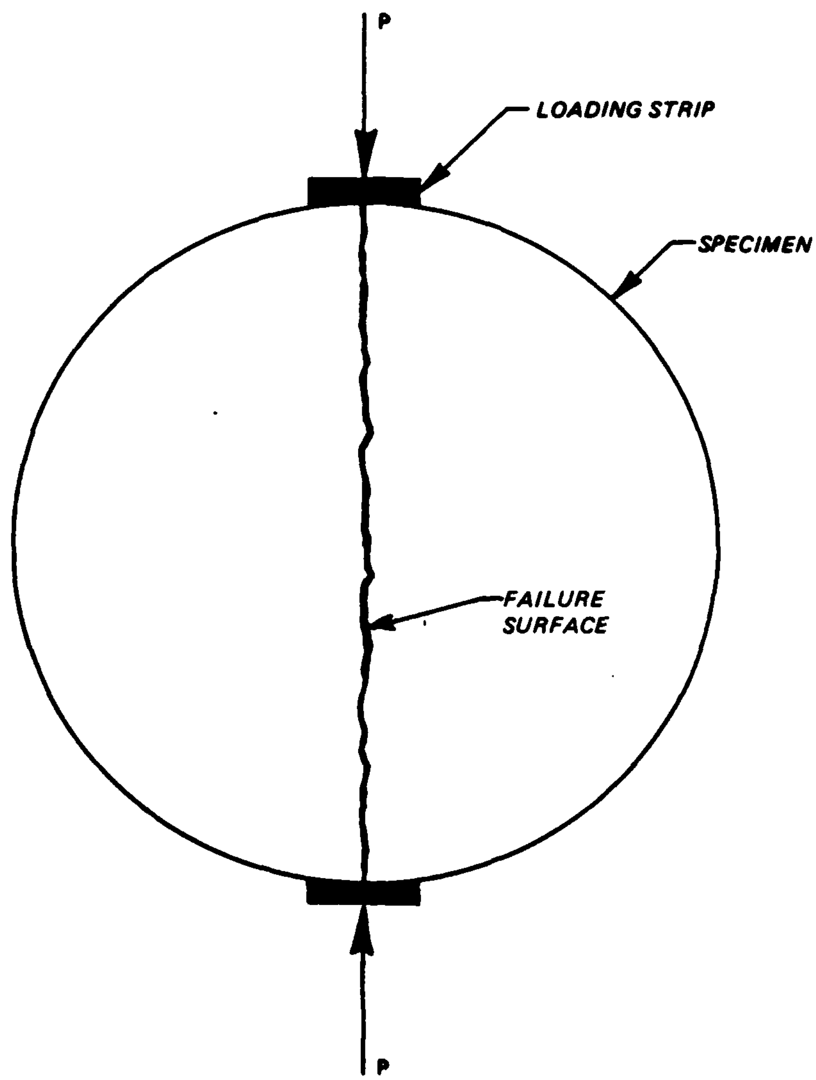

Figure 5. Schematic of the Indirect Tensile Test.

a. Stress along the Vertical Diameter

$$\sigma_{\theta y} = \frac{2P}{\pi at} \left\{ \frac{(1 - r^2/R^2) \sin 2\alpha}{\left[1 - (2r^2/R^2) \cos 2\alpha + r^4/R^4\right]} - \tan^{-1} \left[\frac{(1 + r^2/R^2) \tan \alpha}{(1 - r^2/R^2)} \right] \right\} \tag{6}$$

$$\sigma_{ry} = \frac{-2P}{\pi at} \left\{ \frac{(1 - r^2/R^2) \sin 2\alpha}{\left[1 - (2r^2/R^2) \cos 2\alpha + r^4/R^4\right]} + \tan^{-1} \left[\frac{(1 + r^2/R^2) \tan \alpha}{(1 - r^2/R^2)} \right] \right\} \tag{7}$$

$$\tau_{r\theta} = 0 \tag{8}$$

b. Stress along the Horizontal Diameter

$$\sigma_{\theta x} = \frac{-2P}{\pi at} \left\{ \frac{(1 - r^2/R^2) \sin 2\alpha}{\left[1 + (2r^2/R^2) \cos 2\alpha + r^4/R^4\right]} + \tan^{-1} \left[\frac{(1 - r^2/R^2) \tan \alpha}{(1 + r^2/R^2)} \right] \right\} \tag{9}$$

$$\sigma_{rx} = \frac{2P}{\pi at} \left\{ \frac{(1 - r^2/R^2) \sin 2\alpha}{\left[1 + (2r^2/R^2) \cos 2\alpha + r^4/R^4\right]} - \tan^{-1} \left[\frac{(1 - r^2/R^2) \tan \alpha}{(1 + r^2/R^2)} \right] \right\} \tag{10}$$

$$\tau_{\theta r} = 0 \tag{11}$$

where

$\sigma_{\theta y}$ = tangential stress along the y or vertical axis

P = applied load

a = load strip width

t = specimen thickness or height

r = radial distance from specimen center

R = radius of specimen

α = radian measure of angle due to loading strip

$= \frac{a}{2R}$

σ_{ry} = radial stress

τ = shear stresses along principal planes (vertical and horizontal diameters)

$\sigma_{\theta x}$ = tangential stress along the x or horizontal axis

σ_{rx} = radial stress

Figure 6 shows these typical stresses and their distribution on horizontal and vertical principal axes; stresses shown on the figure are one-half of the actual values.

For disc-shapes such as those of Marshall specimens, plane stress conditions apply; that is, there is no applied stress in the Z or thickness direction. From the theory of elasticity, the following strain equations are true for this geometry.

$$\varepsilon_x = \frac{1}{E} (\sigma_{rx} - \upsilon\sigma_{\theta x}) \tag{12}$$

$$\varepsilon_y = \frac{1}{E} (\sigma_{ry} - \upsilon\sigma_{\theta y}) \tag{13}$$

Rearranging the equations and integrating along the diameters gives

$$E = \frac{1}{H} \left(\int_{-R}^{R} \sigma_{rx} \, dr - \upsilon \int_{-R}^{R} \sigma_{\theta x} \, dr \right) \tag{14}$$

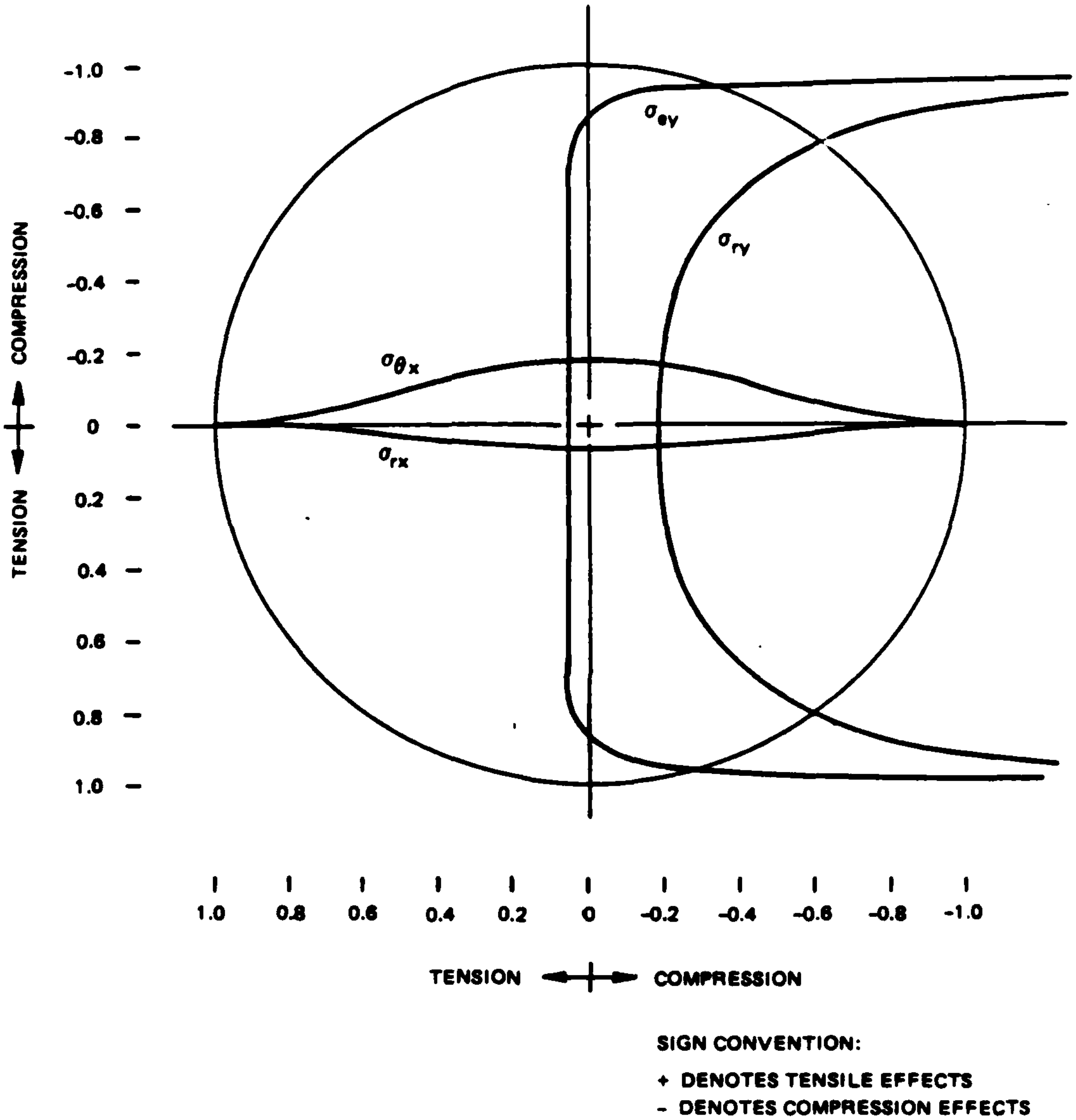

Figure 6. Stress Distribution along Principal Axes of Specimen during Indirect Tensile Test (Stresses Shown are One-Half of Actual Values).

$$E = \frac{1}{H}\left(\int_{-R}^{R} \sigma_{ry}\, dr - \upsilon \int_{-R}^{R} \sigma_{\theta y}\, dr\right) \tag{15}$$

where

ε_x = strain in the x or horizontal axis

E = modulus of elasticity or Young's modulus (in either the x- or y-direction)

υ = Poisson's ratio

ε_y = strain in the y or vertical axis

H = horizontal diameter deformation during testing

2. Static and Repetitive Load Tensile Testing

The indirect tensile test is performed in either a static or repetitive mode. The static mode is performed by increasing the applied load until the specimen fails in tension. From the static test, the tensile stress is calculated at the maximum load and the tensile strength is defined as the tensile stress at this maximum or failure load. Similarly, the static modulus of elasticity is found by using failure conditions.

The resilient test mode provides estimates of resilient moduli of elasticity when loads from 10 to 50 percent of the splitting load are applied. Figure 7 shows how loads and deformations are determined from recorded data. The total resilient modulus is based on an applied load and deformations occurring during loading. The instantaneous resilient modulus is based on resilient deformations that occur on unloading or on instantaneous rebound of the specimen.

3. Equations Developed for this Study

Numerical integration of Equations (14) and (15) and other mathematical operations produce the following approximate equations for 4-inch-diameter Marshall specimens loaded with a strip 1/2 inch wide (R = 2 inches and a = 1/2 inch).

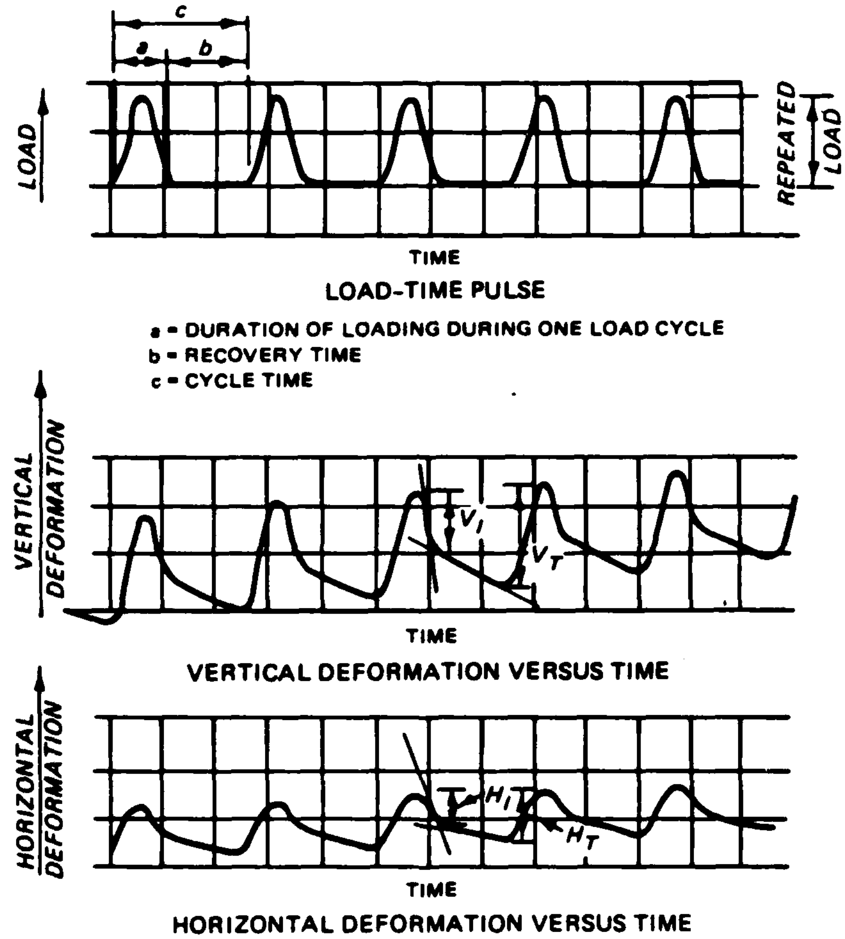

Figure 7. Resilient Indirect Tensile Traces and Measurements (Reference 12).

$$E = -3.54 \left(\frac{P}{tV}\right) \quad (16)$$

$$\upsilon = -3.55 \left(\frac{H}{V}\right) -0.27 \quad (17)$$

$$\sigma_t = 0.156 \left(\frac{P}{t}\right) \quad (18)$$

$$\sigma_c = 0.474 \left(\frac{P}{t}\right) \quad (19)$$

where

V = vertical diameter deformation during testing

σ_t = tensile stress at the specimen center when loaded to failure

σ_c = compressive stress at the specimen center

υ, t, P, E, and H have been previously explained in this section

Equations (16) and (17), the Young's modulus, and the Poisson ratio equations developed for this study can be used for both resilient and static testing. These equations are not the same as those recommended in ASTM D 4123 and Reference 19. They are similar, however, to those used at Purdue University.* Equations (18) and (19) are the familiar equations for tensile and compressive stresses at the center of the specimen.

B. DIRECT SHEAR TEST

Direct shear tests, although routinely performed on materials such as soils and rock, are not common in asphalt pavement work. Generally, each specimen is placed in a shearing apparatus, a normal load is applied to the specimen, and the specimen is sheared. The normal and shear loads and shear deformation are recorded. Loads are converted into average stresses by dividing by contact area.

For this study, shear testing was performed on Marshall sized specimens of asphalt mix. All specimens were disc shaped with diameters equal to 4 inches and approximate heights of 2-1/2 inches.

Equations used for this testing were as follows:

$$\tau = \frac{S}{\pi R^2} \quad (20)$$

---

* Personal communication between E. R. Brown of WES and Professor Leonard Wood of Purdue University, March 1985.

$$\sigma = \frac{N}{\pi R^2} \tag{21}$$

where

τ = shear stress on the failure plane

S = maximum shearing load

R = specimen radius

σ = normal stress on the failure plane

N = normal load on the test specimen

C. ACCELERATED AGING TEST

Asphalt mixes age or harden with time after exposure to the environment. Actually, the asphalt cement ages from loss of volatiles, exposure to sunlight, and other natural forces. In a previous study (Reference 20), an accelerated aging test was developed for laboratory use on mixes either to supplement conventional Marshall mix designs or to aid in selecting an asphalt cement providing better resistance to age hardening. An asphalt cement maintaining a high percentage of its unaged consistency, after aging, is desirable.

The penetration test (ASTM D5) performed on recovered aged asphalt was the basis for determining damage caused by aging. As shown in Figure 8, asphalt cement has a known or identifiable penetration when delivered from a refinery. Heating and mixing with aggregate causes a loss in penetration or hardening. After pavement construction, environmental forces cause additional hardening

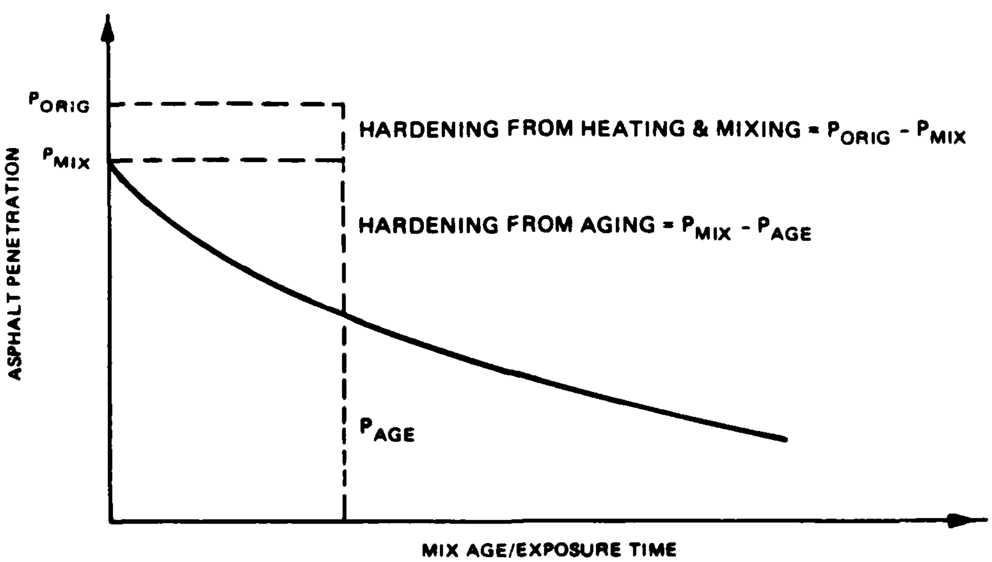

Figure 8. Asphalt Hardening as a Result of Age.

or aging. At varying times after pavement construction, this aging can be noted by decreasing values of asphalt penetration.

Figure 9 illustrates the use of a ratio of asphalt penetrations to show changes in asphalt mix durability with environmental exposure. The durability index is a ratio of asphalt penetration after accelerated aging to its original unaged penetration. The figure shows that this accounts for the constant heating and mixing penetration loss which is a function of mix production, and a variable aging loss which is a function of exposure conditions after construction.

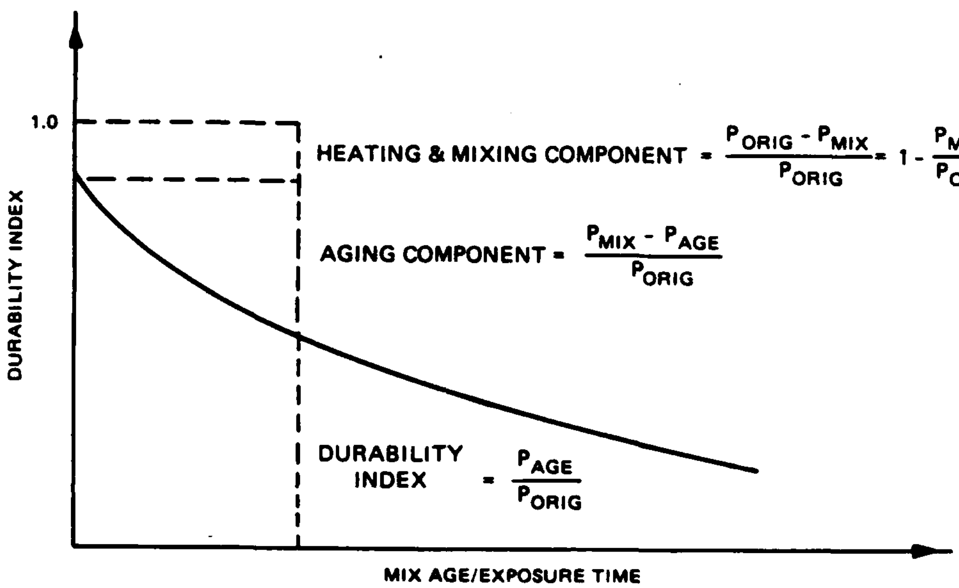

Figure 9. Asphalt-Hardening Indices Based on Penetration.

Reference 20 showed that an asphalt mix exposed to 7 days of constant 225 °F oven heat would produce aging equivalent to about 10 to 15 years of environmental exposure in moderate climates of this country.

This concept of asphalt mix durability index and accelerated aging was also used in this study. Basically, a lower durability index indicates an increased amount of asphalt age-hardening, assuming a constant amount of hardening as a result of heating and mixing.

D. CREEP TEST

During the service life of flexible pavements, rutting can occur. When it occurs, it can be placed into one of the following categories:

1. Deep-Seated Rutting in Lower Pavement Layers

This occurs in the base, subbase, or subgrade. The cause can be linked to overload, inadequate compaction, or seasonal periods of low strength, such as spring thaw.

2. Shallow Rutting in Upper Pavement Layers

These movements can be traced to nonrecoverable, traffic-induced deformations in the asphalt surface layers. This latter type of rutting is the primary focus of this study.

A study of shallow rutting caused by T-38 aircraft traffic indicated a relationship between mix properties used in design and observed rutting in surface mixes (Reference 14). Paving mixes from taxiways at seven Air Force bases were sampled and studied. All mixes had been designed with the 75 blow per side hammer-compactive effort and had experienced high-volume 240 psi contact pressure traffic. A visual rutting classification was used to supplement field sampling and laboratory test results. Laboratory recompaction results, with the gyratory compactor, showed that in-place after-traffic densities in traffic lanes could be approximated.

Figure 10 shows a bar graph of data taken from this study pointing out that observed rutting potential can be indicated by average voids filled with asphalt of the two uppermost recompacted pavement layers. Averages of about 71-, 76-, and 80-percent voids filled indicated none, slight, and severe rutting, respectively.

Creep testing has been used by many organizations for trying to quantify rutting potential of asphalt concrete mixes. It is usually performed during the design phase. The idea is to eliminate high-creep mixes that rut easily. Creep testing is concerned with time-related deformation of asphalt mixes. Creep testing can be divided into two groups, dynamic and static testing, each with confined and unconfined subgroups. The dynamic-confined tests are the most complicated but seem to more closely represent behavior under traffic. They require complex testing equipment, procedures, and data analysis.

The static-unconfined test was used in this study for simplicity of method and equipment.

During the past few years, the creep test has been used to predict permanent deformations and to rank mix behavior. The Shell International Petroleum Company of Amsterdam, The Netherlands, developed a pavement design procedure that includes creep testing of bituminous mixes. Results are used in conjunction with nomographs, charts, formulas, and computations to estimate or predict permanent deformations in the asphalt layers (Reference 21).

Most users of creep tests recommend that data be used only to provide relative measures of mix behavior. One user, the North Dakota State Highway Department, has reported extensive laboratory testing of old and new asphalt mixes. Based on the Shell procedure and rut-depth data, North Dakota found that actual and predicted permanent deformations did not correlate well. North Dakota, however, reported its planned adoption of the creep test as a supplement to routine Marshall mix design and evaluation work (Reference 22).

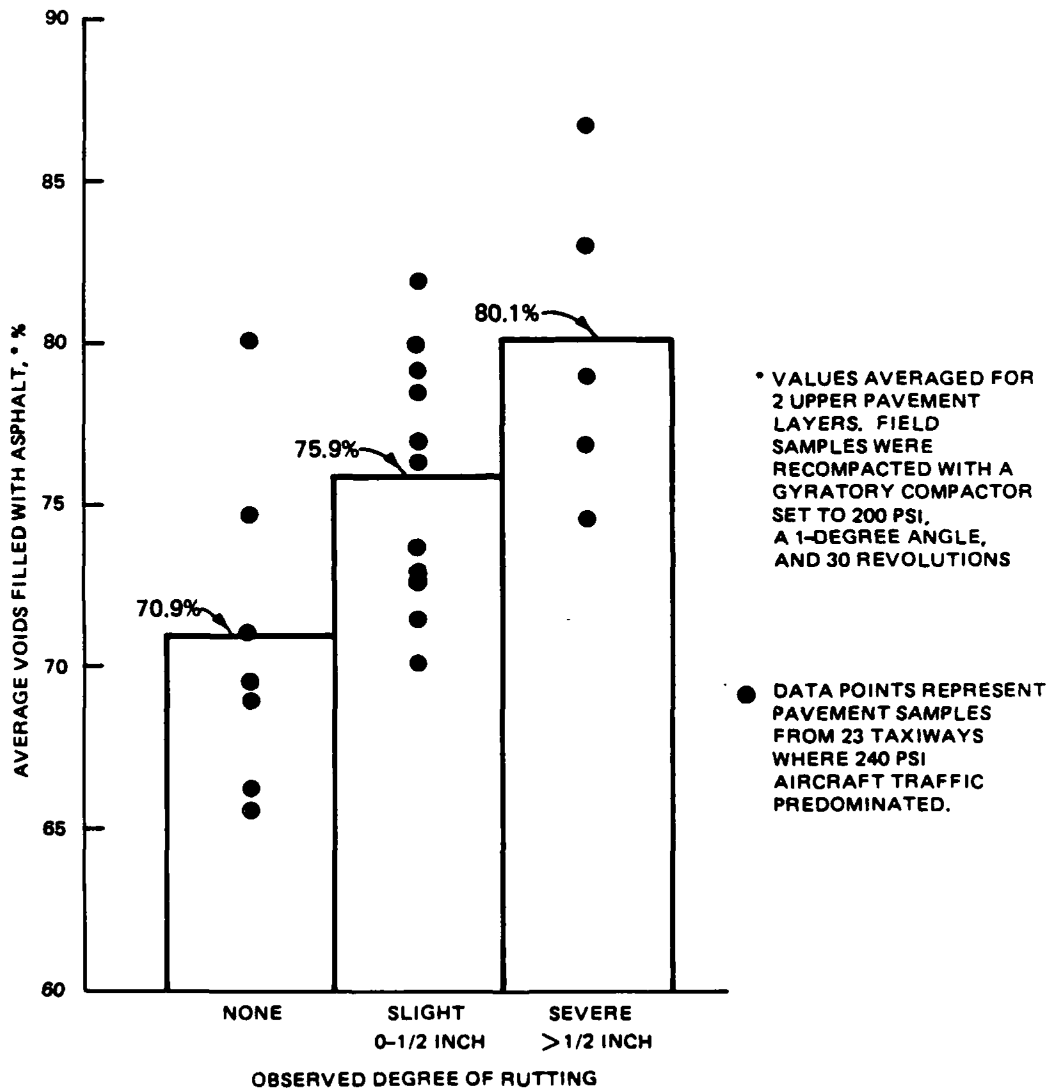

Figure 10. Surface Rutting of Taxiway Mixes Subjected to T-38 Aircraft Traffic.

SECTION V

EQUIPMENT AND PROCEDURES

Several types of test procedures were required for this study. In addition to the standard laboratory equipment and procedures used to perform Marshall mix designs, more sophisticated and complex equipment and fundamental testing schemes were needed, including use of the gyratory compactor to produce test specimens, modulus of elasticity, shear and tensile strength evaluation, accelerated aging, and creep testing of the specimens.

The following paragraphs outline equipment and procedures used in this investigation. Apparatus and procedures are given, based on the type of testing performed.

A. MARSHALL AND GYRATORY TESTING

Marshall and gyratory testing procedures and equipment have been discussed in Section III of this report. Marshall procedures are followed after laboratory mixing and compacting with the 10-pound manually operated hammer. For this investigation, the 75 blow per side compactive effort was used as the control because of its current standardization for high-contact pressure, heavy-duty asphalt mixes.

Previous experience with gyratory compaction (References 13 and 14) suggests that laboratory tests, when performed on mixes compacted at stresses similar to anticipated field traffic conditions, simulate field behavior under traffic. Based on these experiences, a gyratory compactor, Model 4-C, modified to exert in excess of 400 psi normal stress, was used to produce test specimens. Compactive efforts on the gyratory compactor were varied by changing normal compaction stresses from 100 to 400 psi in 100 psi increments. All compaction was done at 1-degree gyration angle for 30 revolutions of the machine. Figure 11 shows the modified gyratory compactor.

B. INDIRECT TENSILE TESTING

Static and repeat-load indirect tensile tests were performed, using the same basic equipment. Figures 12 and 13 show overall and closeup views of the testing equipment. A closed-loop MTS® electro-hydraulic testing system was used. Disc-shaped specimens of asphalt mix 4 inches in diameter, normally 2-1/2 inches thick, were loaded through 1/2 inch wide loading strips. Loads and vertical and horizontal deformations were recorded for each test on appropriate recording equipment.

The choice of recording equipment depended on the type of test performed.

1. Repeated Load Testing

Repeated-load testing required the use of at least a three-channel strip chart recorder. Load was measured on one channel, vertical deformation from actuator movement was recorded on a second channel, and total horizontal

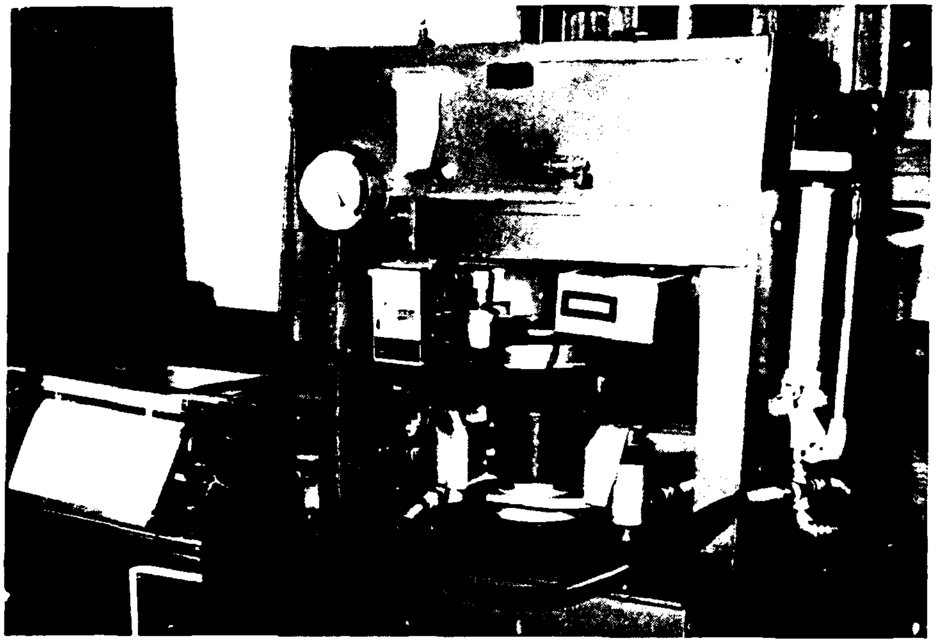

Figure 11. Modified Model 4C Gyratory Compactor.

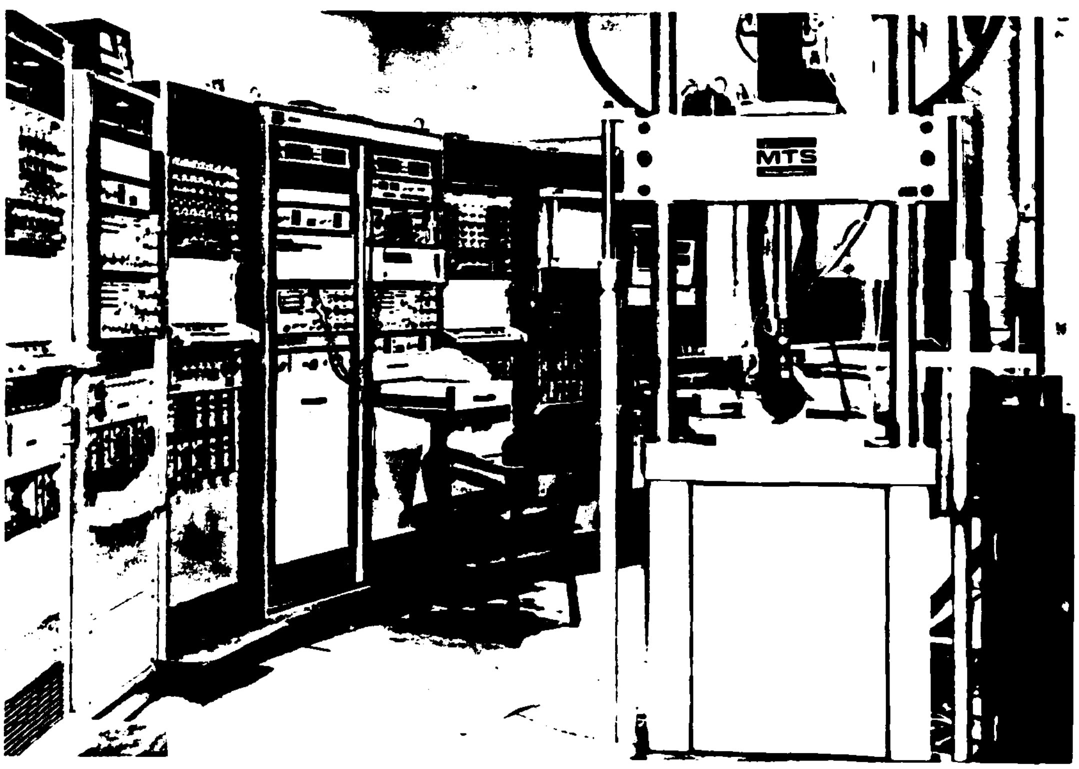

Figure 12. Overall View of Test Equipment and Indirect Tensile Apparatus.

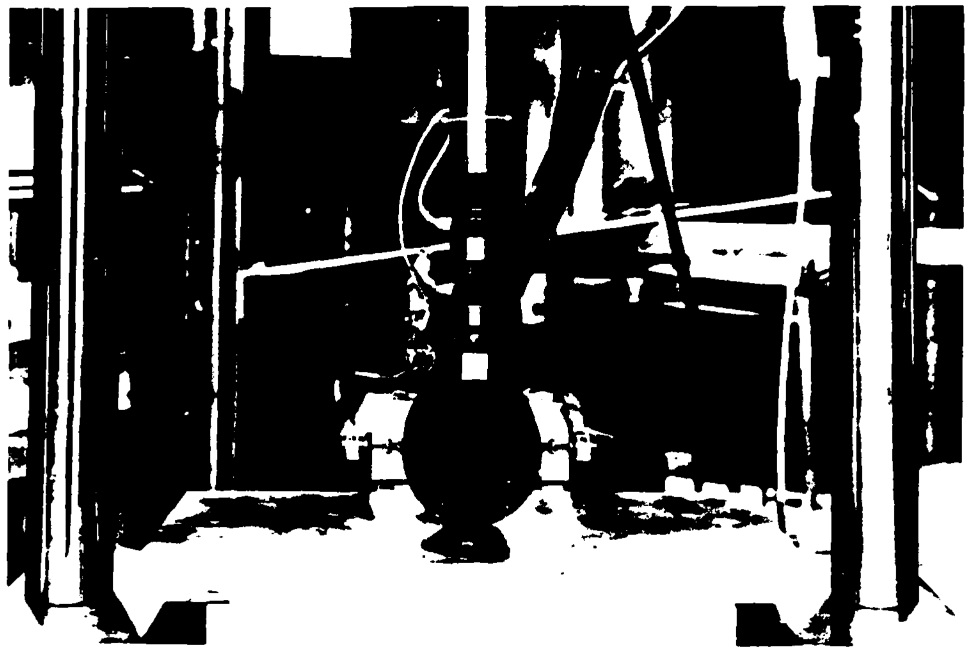

Figure 13. Closeup of Indirect Tensile Apparatus.

deformation from spring-loaded linear variable differential transformers (LVDTs) was recorded on the third channel. Each specimen was tested at two positions, an initial position (0 degrees) followed by a position at right angles (90 degrees) to the original position. A total of three specimens were tested at each asphalt content; reported results were the average values of six measurements.

2. Static Testing

Static testing to failure in tension required use of either two X-Y plotters or one X-Y-Y plotter. Both types were used at various times during this study. The two X-Y plotters, with single pens, produced two data sheets with load versus vertical deformation and load versus horizontal deformation. The X-Y-Y plotter, with two pens, produced separate plots of load versus vertical deformation and horizontal deformation on a single data sheet. The two-pen plotter was more efficient for data storage purposes. All recorders were Hewlett-Packard equipment. A total of three specimens was similarly tested at each asphalt content; reported results were averages of three measurements.

The same load cell and hydraulic actuator were used for both types of testing. A 5,000-pound load cell was mounted on the end of a 3,300-pound MTS® actuator; the actuator's internal LVDT was used to monitor vertical deformation.

Specimens were tested at two temperatures for each type of test. The first tests were performed at room temperature, 77 °F. Elevated temperature tests were performed by heating asphalt mix specimens to 104 °F for at least

2 hours before testing. Specimens were removed from an oven and tested in ambient temperature for a maximum of 4 to 5 minutes to minimize any cooling effects on test results.

In general, resilient testing followed techniques outlined in ASTM D 4123 (Reference 12) with exceptions, as previously noted. A loading duration to recovery time interval of 0.1 to 0.9 second was used throughout the resilient testing (see Figure 7). Load was applied using a ramp function triggered by a function generator. A linearly increasing load for 0.05 second was followed by a linearly decreasing load for 0.05 second. This scheme resulted in one load pulse per second. A total of 50-55 loading cycles was applied to each specimen prior to measuring loads and deformations.

C. DIRECT SHEAR TESTING

Direct shear tests were performed with the equipment shown in Figures 14 and 15. The shear testing device consisted of several separate units, as follows.

1. A normal pressure assembly was made of several units designed to maintain a constant normal pressure on specimens during testing. A pressurized tank of nitrogen was used to preset relief pressure on a hydraulic accumulator. A Greer Laer® hydraulic accumulator was placed in line between an Enerpac® Hydraulic Pump (Model P39) and an Enerpac® 10-ton capacity load piston (Model RC 102 AAA). The accumulator allowed the normal hydraulic pressure to remain constant when aggregate particles tended to override each other during application of the shearing load.

2. The simple shear assembly was a platform for testing either 4- or 6-inch diameter disc-shaped asphalt mix specimens. Inserts were used to test 4-inch specimens. Two plates connected by screws formed an interior reaction frame to resist normal forces on the specimen. The device was designed for vertical application of the shear load (Figure 15).

3. A shear deformation measuring device, an LVDT with a total travel of 1/2 inch, was mounted parallel to the direction of shear load application.

4. Shear load measurement was done with a 50,000-pound capacity load cell calibrated and set to 20,000-pound maximum load range. Load was applied through the load cell by a crosshead moving at 1/2 inch per minute.

5. The load-deformation recorder was an X-Y plotter connected to the load cell and the LVDT.

Direct shear tests were conducted at 77 °F. Two normal stresses were used. Stress levels in the vicinity of the 400 psi contact stresses were desirable; however, the very high nitrogen pressures required to preset the accumulator made this dangerous. Instead, 100 and 200 psi normal pressures were used. Test results were averaged from three individual tests at each normal stress level.

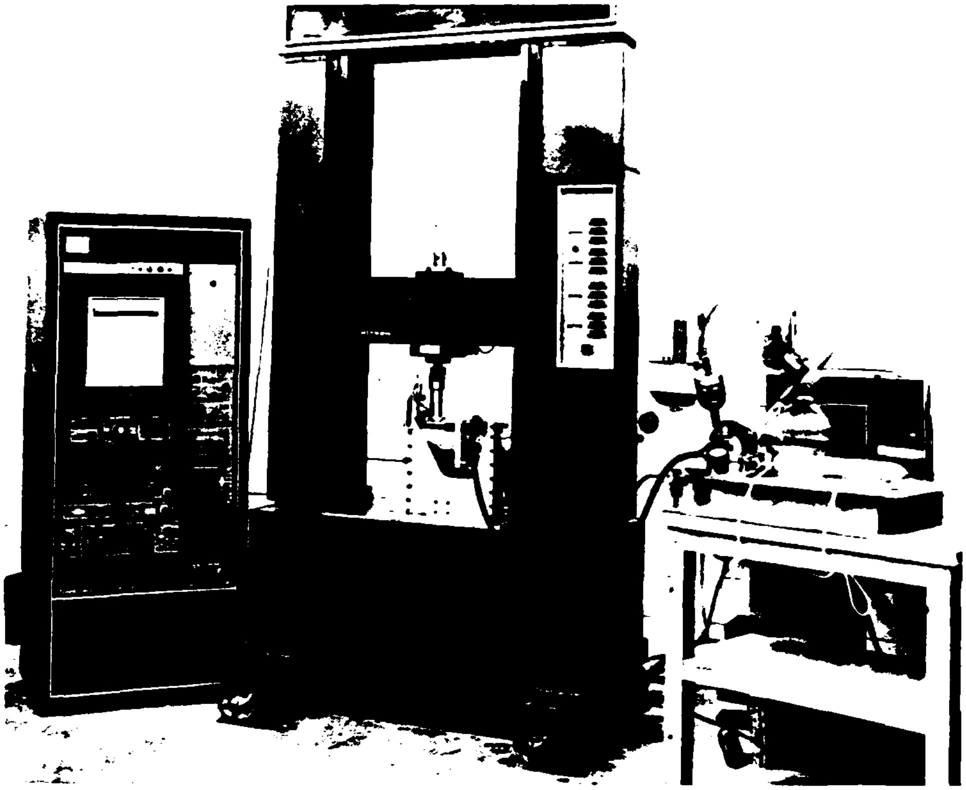

Figure 14. Overall View of Direct Shear Test Equipment.

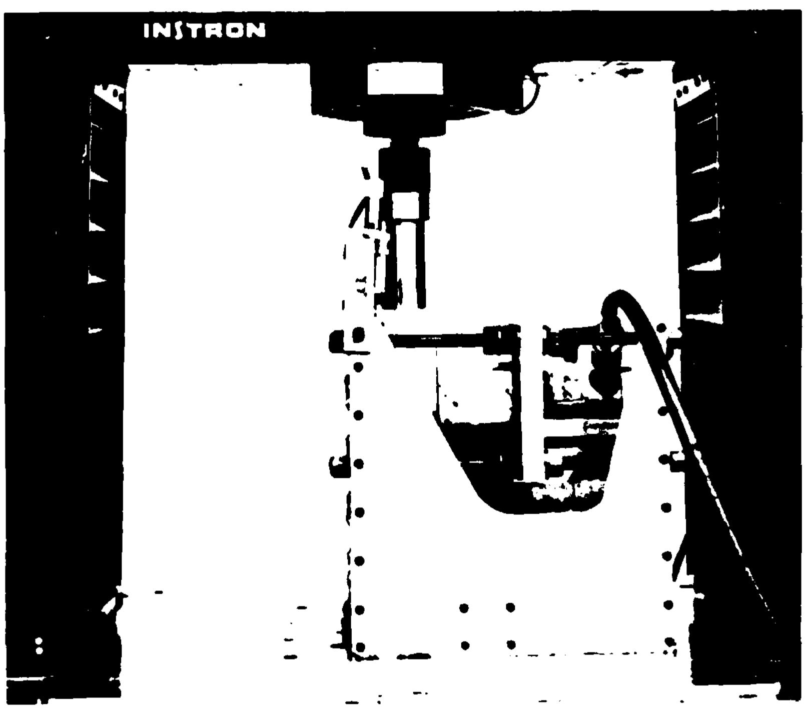

Figure 15. Closeup of Direct Shear Equipment.

D. ACCELERATED AGING TESTING

A previously developed method of laboratory-accelerated aging of asphaltic mixes was used (Reference 20). Marshall-sized specimens were placed in a forced air oven set to 225 °F and aged for 7 days. The aged asphalt was extracted from the mixes and recovered using ASTM Methods D2172 and D1856, respectively (Reference 12). Penetration tests, ASTM D5 (Reference 12), were run on the recovered aged asphalt and compared to original unaged penetration values.

Durability indices, the ratios of aged penetration to unaged penetration, were computed from these test results.

E. CREEP TESTING

The MTS® electro-hydraulic testing system, described previously, was used to perform creep tests; however, it worked in conjunction with an MACSYM 2® data-acquisition and reduction-computer system. A multichannel strip chart recorder was also used to record data in the event of computer malfunction.

A testing procedure was developed for this study since no standard procedure was found in the literature. This procedure was based on the use of three disc-shaped mix specimens of measured height, stacked vertically, and loaded without confinement as shown in Figures 16 and 17. Creep tests were conducted at 77° F.

The table of the load frame was liberally coated with silicone grease before vertically stacking the specimens. Another liberal coat of silicone grease was applied in a 4-inch diameter polished steel loading plate before it was placed on top of the typical 7-1/2-inch high specimen. Silicone grease was used to minimize the effect of end restraint.

A 50- to 60-pound preload or 4 to 5 psi vertical stress was applied to seat the cap on the specimen prior to the application of test loads. Load was applied to the specimens through a steel ball placed on the top loading plate; this avoided any loading eccentricity. The test started with application of a step load to the specimen. Loads corresponding to either 200, 100, 75, or 50 psi vertical stress were applied and held constant throughout the testing period for up to 60 minutes. Vertical loads were held constant without correction for increasing cross-sectional area.

Load and actuator movement (vertical deformation) were monitored and recorded continuously by the strip recorder and intermittently by the computerized data system. Loads and deformations were monitored by the computer system at preselected times after load application; they were converted to stresses and strains simultaneously by the data system. Data sampling times were set at 1, 2, 4, 8, 15, 30, and 60 seconds, continuing similarly until either 60 minutes had elapsed or the specimens had experienced excessive deformation. Excessive deformations are defined as swiftly occurring vertical compression accompanied by tensile cracking and severe bulging of the test specimen.

Figure 16. Creep Test Specimen Ready for Testing.

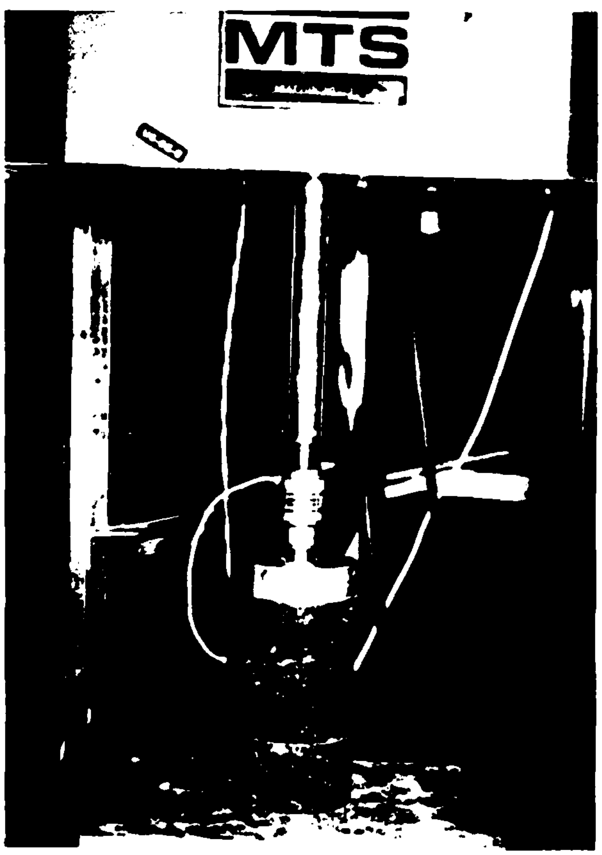

Figure 17. Closeup of Creep Test Specimen.

SECTION VI

RESULTS AND DISCUSSION

A. PRELIMINARY MIX CURVES, PROPERTIES, AND BEHAVIOR

Average results of preliminary specimen fabrication and testing are given in Table 8. Marshall stabilities, flow values, and gyratory stability indices (GSIs) are also shown. Data indicate that Marshall stabilities increased with levels of compaction, at least to the 300 psi level of gyratory compaction. Overall Marshall stabilities for specimens compacted at 400 psi were up to 44 percent higher than those compacted at standard hammer effort. One-inch maximum aggregate mixes showed up to a 27-percent increase at higher compactive efforts and 3/4-inch mixes showed 39-44 percent increased stability.

Table 9 gives best-fit compaction curve constants for the mixes of Table 8. Most of the data had a high correlation coefficient, indicating a good fit to the cubic compaction model presented in Section II. Maximum aggregate densities and corresponding asphalt contents are also given in Table 9.

Figures 18-21 show these aggregate density-asphalt content compaction curves supplemented by zero air voids curves and 85-percent voids filled with asphalt curves. The dashed supplemental curves were computed using the relationships given in Table 5. Compaction stability behavior showed that at the time approximately 85 percent of voids in the mineral aggregate were filled with asphalt, mixes generally became unstable in the gyratory compactor producing GSIs greater than 1.0.

The effects of increased compactive effort can be seen in Figures 18-21. Higher compactive efforts generally decreased the asphalt content required to produce maximum aggregate densities; densities also increased with compactive effort.

Design asphalt contents were determined by using current criteria for heavy-duty mixes (indicated under the 75-blow column of Table 6) with non-absorptive aggregate. Using data in Table 8 for each combination of gradation, asphalt type, and compactive effort, design optimum asphalt contents were determined by averaging the individual asphalt contents satisfying the four criteria given in Part A of Table 6 and checking the mix at the averaged optimum against requirements of Part B. Table 10 lists these heavy-duty optimums along with those optimums indicated by gyratory compactor GSIs.

Comparisons of optimum asphalt contents can be seen in Figures 22 and 23. The figures show that mixes conforming to heavy-duty criteria (currently applied only to 75-blow per side laboratory compacted mixes) are generally leaner than mixes giving maximum aggregate density. This is a reasonable finding because pavements compacted on the lean side of maximum aggregate density are expected to be more tolerant to traffic-related densification than those at higher asphalt contents.

TABLE 8. PRELIMINARY MIX PROPERTIES[a] AND TEST RESULTS.[b]

Mix	Compactive effort	Asphalt content % weight	Total density pcf	Aggregate density pcf	Asphalt content % volume	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Marshall stability pounds	Marshall flow 0.01 in.	Gyratory stability index
3/4-inch aggregate and AC 20	400 psi	3.5	152.0	146.7	8.3	14.9	6.6	55.8	3,534	11	0.95
		4.0	153.0	146.9	9.5	14.7	5.2	64.7	3,252	10	1.00
		4.5	154.1	147.2	10.8	14.6	3.8	74.2	3,402	9	1.00
		5.0	155.5	147.7	12.1	14.2	2.1	85.1	3,368	12	1.17
		5.5	155.2	146.7	13.3	14.9	1.6	89.5	2,601	13	1.55
		6.0	154.9	145.6	14.4	15.4	1.0	93.6	2,185	15	1.93
	300 psi	3.5	151.9	146.6	8.3	14.9	6.6	55.6	2,984	13	1.00
		4.0	153.8	147.6	9.6	14.3	4.7	67.1	3,273	14	1.00
		4.5	154.5	147.5	10.8	14.3	3.5	75.5	3,627	13	1.00
		5.0	155.5	147.7	12.1	14.2	2.1	85.1	3,167	17	1.13
		5.5	155.3	146.8	13.3	14.8	1.5	89.9	2,722	15	1.21
		6.0	155.0	145.7	14.4	15.3	0.9	94.0	2,362	16	1.55
	200 psi	4.0	150.7	144.7	9.4	16.0	6.6	58.6	2,783	12	1.00
		4.5	152.0	145.2	10.6	15.7	5.1	67.7	2,750	14	1.00
		5.0	152.8	145.2	11.9	15.7	3.8	75.6	2,819	14	1.00
		5.5	153.6	145.2	13.1	15.7	2.6	83.6	2,672	14	1.06
		6.0	154.2	144.9	14.4	15.8	1.4	90.0	2,522	15	1.09
		6.5	154.0	144.0	15.5	16.3	0.8	95.0	2,223	17	1.32

[a] Nonabsorptive aggregate used.

[b] Each number reported is usuallv the average of three individual tests or measurements.

TABLE 8. PRELIMINARY MIX PROPERTIES[a] AND TEST RESULTS[b] (CONTINUED).

Mix	Compactive effort	Asphalt content % weight	Total density pcf	Aggregate density pcf	Asphalt content % volume	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Marshall stability pounds	Marshall flow 0.01 in.	Gyratory stability index
3/4-inch aggregate and AC 20 (Continued)	100 psi	4.0	147.4	141.5	9.2	17.9	8.7	51.4	1,659	14	1.00
		4.5	148.9	142.2	10.4	17.4	7.0	59.8	1,839	14	1.00
		5.0	150.0	142.5	11.6	17.2	5.6	67.6	1,740	14	1.00
		5.5	150.9	142.6	12.9	17.2	4.3	75.1	1,789	14	1.00
		6.0	151.7	142.6	14.1	17.1	3.0	82.3	2,093	14	1.00
		6.5	152.2	142.2	15.4	17.4	2.0	88.6	2,000	16	1.00
	75 blow hammer	4.5	150.8	144.0	10.5	16.3	5.8	64.5	2,374	9	--
		5.0	151.7	144.1	11.8	16.3	4.5	72.3	2,219	11	--
		5.5	153.0	144.6	13.1	16.1	3.0	81.6	2,339	11	--
		6.0	153.2	144.0	14.3	16.4	2.1	87.3	2,111	14	--
		6.5	153.0	143.1	15.4	16.9	1.5	91.3	2,175	16	--
		7.0	152.2	141.5	16.5	17.7	1.2	93.0	1,711	20	--
3/4-inch aggregate and AC 40	400 psi	3.0	153.1	148.5	7.1	13.8	6.7	51.5	2,935	12	1.00
		3.5	154.1	148.7	8.3	13.6	5.3	61.0	3,696	11	1.00
		4.0	155.2	149.0	9.6	13.5	3.9	71.1	3,695	13	1.00
		4.5	156.1	149.1	10.8	13.4	2.6	80.7	3,621	13	1.06
		5.0	156.2	148.4	12.0	13.8	1.8	87.2	3,185	14	1.26
		5.5	155.7	147.1	13.0	14.5	1.3	90.8	2,496	17	1.75

TABLE 8. PRELIMINARY MIX PROPERTIES[a] AND TEST RESULTS[b] (CONTINUED).

Mix	Compactive effort	Asphalt content % weight	Total density pcf	Aggregate density pcf	Asphalt content % volume	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Marshall stability pounds	Marshall flow 0.01 in.	Gyratory stability index
3/4-inch aggregate and AC 40 (Continued)	300 psi	3.5	151.2	145.9	8.2	15.3	7.1	53.5	3,156	13	1.00
		4.0	152.5	146.9	9.4	15.0	5.6	62.8	3,401	15	1.00
		4.5	154.1	147.2	10.7	14.5	3.8	73.6	3,369	15	1.00
		5.0	155.2	147.4	12.0	14.4	2.4	83.3	3,445	14	1.03
		5.5	155.1	146.6	13.1	14.8	1.7	88.4	3,267	16	1.15
		6.0	155.0	145.7	14.3	15.3	1.0	93.2	2,596	18	1.42
	200 psi	4.5	150.1	143.3	10.4	16.7	6.3	62.2	2,428	13	1.00
		5.0	151.5	143.9	11.7	16.4	4.7	71.2	2,462	13	1.00
		5.5	152.6	144.2	12.°	16.2	3.3	79.6	2,827	14	1.00
		6.0	153.0	143.8	14.1	16.4	2.3	85.9	2,775	15	1.03
		6.5	153.6	143.6	15.4	16.6	1.2	92.8	2,730	16	1.16
		7.0	152.9	142.2	16.5	17.4	0.9	94.8	2,265	20	1.40
	100 psi	4.5	146.7	140.1	10.2	18.6	8.4	54.7	1,653	16	1.00
		5.0	147.7	140.3	11.4	18.5	7.1	61.5	1,701	15	1.00
		5.5	149.8	141.6	12.7	17.8	5.1	71.3	1,958	16	1.00
		6.0	149.9	140.9	13.9	18.2	4.3	76.5	2,012	16	1.00
		6.5	150.8	141.0	15.1	18.1	3.0	83.4	2,077	17	1.00
		7.0	152.1	141.5	16.4	17.8	1.4	91.9	2,326	19	1.08

TABLE 8. PRELIMINARY MIX PROPERTIES[a] AND TEST RESULTS[b] (CONTINUED).

Mix	Compactive effort	Asphalt content % weight	Total density pcf	Aggregate density pcf	Asphalt content % volume	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Marshall stability pounds	Marshall flow 0.01 in.	Gyratory stability index
3/4-inch aggregate and AC 40 (Continued)	75 blow hammer	4.5	149.0	142.3	10.3	17.3	7.0	59.6	2,148	10	--
		5.0	150.3	142.8	11.6	17.0	5.4	68.1	2,232	11	--
		5.5	151.2	142.9	12.8	17.0	4.2	75.4	2,352	13	--
		6.0	151.9	142.8	14.1	17.1	3.0	82.5	2,438	13	--
		6.5	152.5	142.6	15.2	17.2	2.0	88.6	2,521	15	--
		7.0	152.1	141.5	16.4	17.8	1.4	91.9	2,323	20	--
1-inch aggregate and AC 20	400 psi	3.0	152.7	148.1	7.1	13.9	6.8	50.9	3,173	14	1.00
		3.5	152.6	147.3	8.3	14.5	6.2	57.3	3,072	12	1.00
		4.0	154.9	148.7	9.6	13.6	4.0	70.6	3,215	12	1.00
		4.5	154.9	147.9	10.8	14.0	3.2	76.9	2,921	13	1.00
		5.0	155.0	147.3	12.0	14.4	2.4	83.2	3,114	12	1.00
		5.5	156.1	147.5	13.3	14.3	1.0	93.1	3,092	17	1.30
	300 psi	3.0	154.5	149.9	7.2	12.9	5.7	55.6	3,876	17	1.00
		3.5	156.3	150.8	8.5	12.4	3.9	68.6	3,932	14	1.00
		4.0	157.2	150.9	9.8	12.4	2.6	79.1	3,428	15	1.00
		4.5	157.4	150.3	11.0	12.7	1.7	86.7	3,264	15	1.06
		5.0	157.8	149.9	12.3	13.0	0.7	94.8	2,732	15	1.34
		5.5	156.9	148.3	13.4	13.9	0.5	96.6	2,487	18	1.35

TABLE 8. PRELIMINARY MIX PROPERTIES[a] AND TEST RESULTS[b] (CONTINUED).

Mix	Compactive effort	Asphalt content % weight	Total density pcf	Aggregate density pcf	Asphalt content % volume	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Marshall stability pounds	Marshall flow 0.01 in.	Gyratory stability index
1-inch aggregate and AC 20 (Continued)	200 psi	3.0	154.3	149.7	7.2	13.1	5.9	55.0	2,510	13	1.00
		3.5	155.3	149.9	8.4	12.9	4.5	65.2	2,946	12	1.00
		4.0	155.7	149.5	9.7	13.2	3.5	73.4	2,800	13	1.00
		4.5	156.9	149.8	11.0	13.0	2.0	84.6	3,336	15	1.00
		5.0	156.9	149.1	12.1	13.3	1.2	90.8	2,749	15	1.11
		5.5	156.7	148.1	13.4	14.0	0.6	95.7	2,305	18	1.24
	100 psi	4.0	152.6	146.5	9.5	14.9	5.4	63.6	1,784	15	0.95
		4.5	151.3	144.5	10.6	16.1	5.5	65.8	1,792	16	0.97
		5.0	152.9	145.3	11.9	15.7	3.8	76.0	2,103	19	1.00
		5.5	154.8	146.3	13.2	15.0	1.8	88.0	2,100	19	1.05
		6.0	155.5	146.2	14.5	15.1	0.6	96.0	2,161	23	1.05
		6.5	154.4	144.4	15.6	16.2	0.6	96.5	2,004	21	1.08
	75 blow hammer	3.5	152.8	147.5	8.3	14.3	6.0	57.9	3,365	12	--
		4.0	154.3	148.1	9.6	14.0	4.4	68.7	2,710	12	--
		4.5	154.6	147.6	10.8	14.2	3.4	75.9	2,650	14	--
		5.0	155.0	147.3	12.0	14.4	2.4	83.2	3,829	13	--
		5.5	154.9	146.4	13.2	14.9	1.7	88.3	2,637	13	--
		6.0	155.2	145.9	14.5	15.3	0.8	94.8	2,155	21	--

TABLE 8. PRELIMINARY MIX PROPERTIES[a] AND TEST RESULTS[b] (CONTINUED).

Mix	Compactive effort	Asphalt content % weight	Total density pcf	Aggregate density pcf	Asphalt content % volume	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Marshall stability pounds	Marshall flow 0.01 in.	Gyratory stability index
1-inch aggregate and AC 40	400 psi	3.0	155.5	150.4	7.2	12.7	5.5	56.8	3,694	13	1.00
		3.5	154.8	149.4	8.3	13.2	4.9	63.1	3,034	12	1.00
		4.0	156.3	150.0	9.6	12.8	3.2	75.0	3,506	14	1.00
		4.5	157.2	150.1	10.9	12.8	1.9	85.2	3,791	12	1.00
		5.0	157.3	149.4	12.1	13.2	1.1	91.8	3,267	14	1.13
		5.5	157.0	148.4	13.3	13.8	0.5	96.3	2,555	16	1.80
	300 psi	3.5	153.4	148.0	8.3	14.1	5.8	59.0	3,059	13	1.00
		4.0	153.0	146.9	9.4	14.6	5.2	64.2	2,779	13	1.00
		4.5	153.9	147.0	10.7	14.7	4.0	72.9	2,890	14	1.00
		5.0	155.1	147.3	11.9	14.4	2.5	82.9	3,073	13	1.00
		5.5	156.2	147.6	13.2	14.4	1.2	92.8	3,086	13	1.12
		6.0	155.4	146.1	14.4	15.2	0.8	94.8	2,400	16	1.34
	200 psi	3.5	154.0	148.6	8.3	13.7	5.4	60.7	2,368	12	1.00
		4.0	154.3	148.1	9.5	14.0	4.5	68.1	2,505	16	1.00
		4.5	156.2	149.2	10.8	13.3	2.5	81.1	2,678	12	1.00
		5.0	156.6	148.8	12.1	13.6	1.5	89.0	2,777	16	1.00
		5.5	156.3	147.7	13.2	14.2	1.0	93.2	2,550	18	1.17
		6.0	155.9	146.5	14.4	14.9	0.5	96.9	2,318	19	1.25

TABLE 8. PRELIMINARY MIX PROPERTIES[a] AND TEST RESULTS[b] (CONCLUDED).

Mix	Compactive effort	Asphalt content % weight	Total density pcf	Aggregate density pcf	Asphalt content % volume	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Marshall stability pounds	Marshall flow 0.01 in.	Gyratory stability index
1-inch aggregate and AC 40 (Continued)	100 psi	5.0	150.7	143.2	11.6	16.8	5.2	68.9	1,748	14	1.00
		5.5	150.5	142.2	12.8	17.5	4.7	73.3	1,583	15	1.00
		6.0	151.6	142.5	14.0	17.2	3.2	81.4	1,685	15	1.00
		6.5	152.1	142.2	15.2	17.4	2.2	87.6	1,849	15	1.00
		7.0	152.7	142.0	16.5	17.5	1.0	94.1	2,141	16	1.00
		7.5	152.7	141.2	17.6	17.9	0.3	98.3	2,261	20	1.07
	75 blow hammer	3.5	154.6	149.2	8.3	13.3	5.0	62.5	3,007	12	--
		4.0	154.6	148.4	9.5	13.7	4.2	69.1	2,802	11	--
		4.5	154.6	147.6	10.7	14.2	3.5	75.3	2,993	14	--
		5.0	155.8	148.0	12.0	14.0	2.0	85.6	2,642	16	--
		5.5	155.9	147.3	13.2	14.4	1.2	91.6	2,224	17	--
		6.0	155.4	146.0	14.4	15.2	0.8	94.8	2,171	23	--

TABLE 9. CUBIC REGRESSION CURVES AND MAXIMUM AGGREGATE DENSITIES FOR ALL COMPACTIVE EFFORTS.[a]

Mix	Effort	a_0	a_1	a_2	a_3	R^2	Maximum density coordinates: Asphalt content, % weight	Maximum density coordinates: Aggregate, pcf
3/4-inch aggregate and AC 20	400	175.8	-22.39	5.6032	-0.451851	0.9362	4.89	147.46
	300	125.2	10.39	-1.2952	0.022221	0.9625	4.54	147.75
	200	144.8	2.55	1.0476	-0.103703	0.9772	5.14	145.31
	75	158.3	-11.82	2.9540	-0.229629	0.9852	5.40	144.45
	100	124.9	7.11	-0.8286	0.022221	0.9894	5.51	142.64
1-inch aggregate and AC 20	400	150.2	-2.00	0.6633	-0.072402	0.6220	3.40	148.22
	300	131.1	10.91	-1.6968	0.051851	0.9734	3.91	150.88
	200	161.9	-10.32	2.8857	-0.266666	0.9435	3.94	149.73
	75	101.5	29.15	-5.8905	0.377776	0.9812	4.06	148.03
	100	411.9	-157.53	30.6143	-1.955558	0.9670	5.83	146.54
3/4-inch aggregate and AC 40	400	164.2	-14.24	4.1841	-0.392593	0.9947	4.28	149.12
	300	123.2	10.81	-1.3095	0.022221	0.9806	4.69	147.39
	200	142.4	-3.59	1.4429	-0.133333	0.9649	5.62	144.14
	75	152.6	-8.67	2.1539	-0.162962	0.9724	5.70	143.29
	100	64.2	38.73	-6.4968	0.362962	0.6834	6.14	141.09
1-inch aggregate and AC 40	400	200.6	-38.18	9.4508	-0.770370	0.9045	4.54	149.97
	300	264.1	-76.35	16.3809	-1.155554	0.9786	5.28	147.55
	200	181.5	-24.59	6.0111	-0.481482	0.8932	4.70	148.75
	75	223.8	-48.37	10.3000	-0.733335	0.9702	4.68	147.85
	100	272.9	-63.27	10.2065	-0.548154	0.9460	6.42	142.34

[a]Data from Table 8 were used with the following regression model:

$\gamma_{ag} = a_0 + a_1(AC) + a_2(AC)^2 + a_3(AC)^3$.

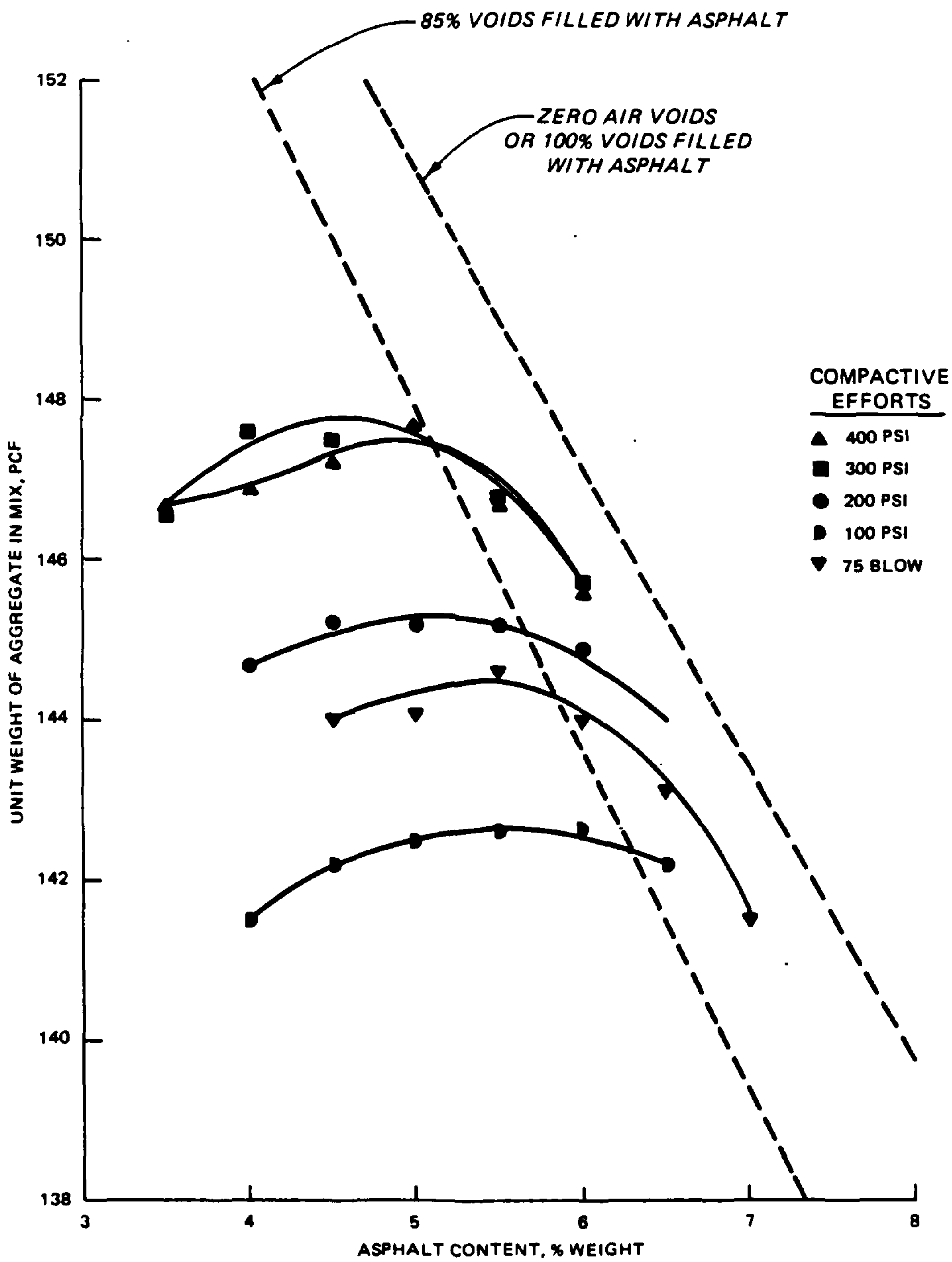

Figure 18. Compaction Curves, 3/4-Inch and AC 20 Mixes.

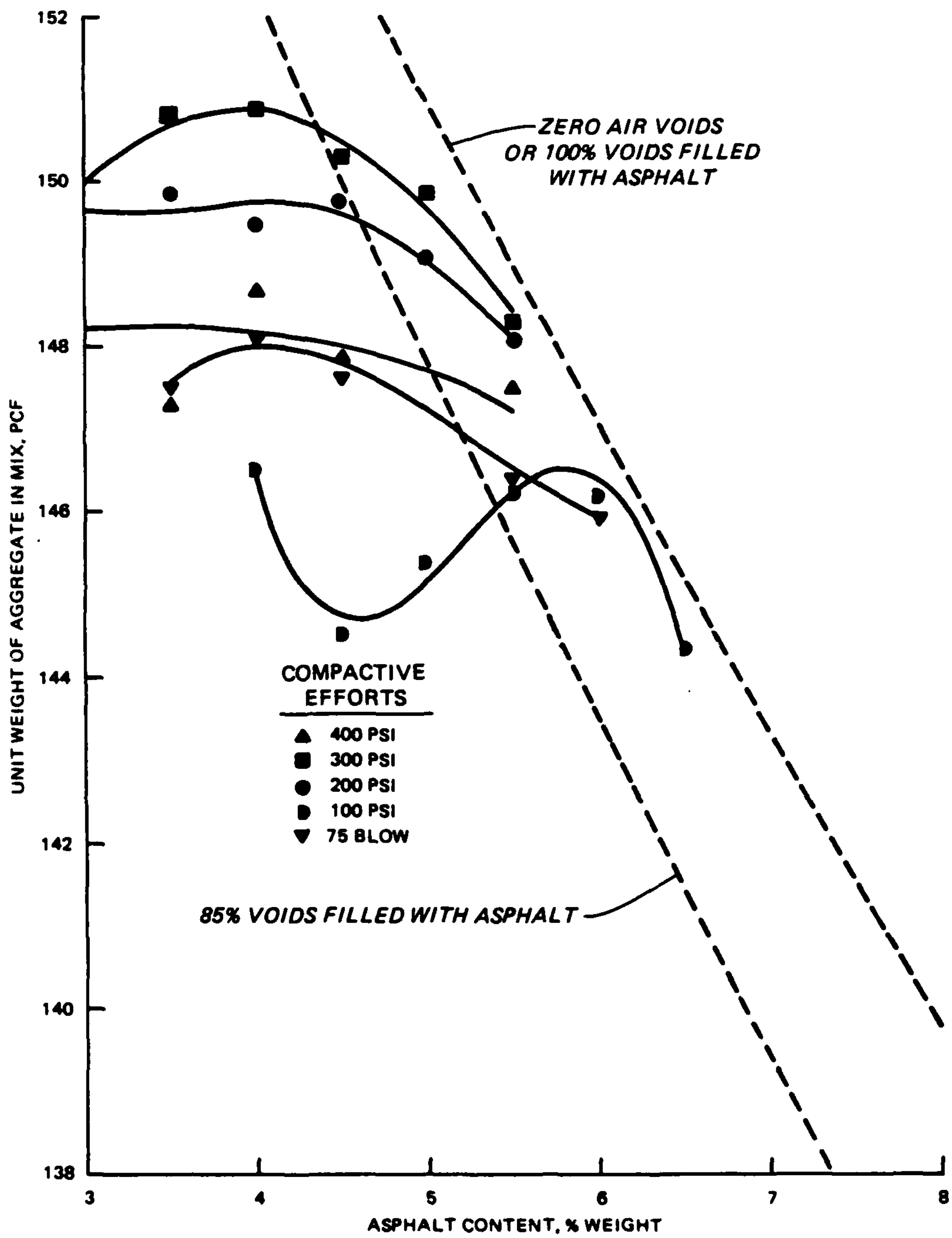

Figure 19. Compaction Curves, 1-Inch and AC 20 Mixes.

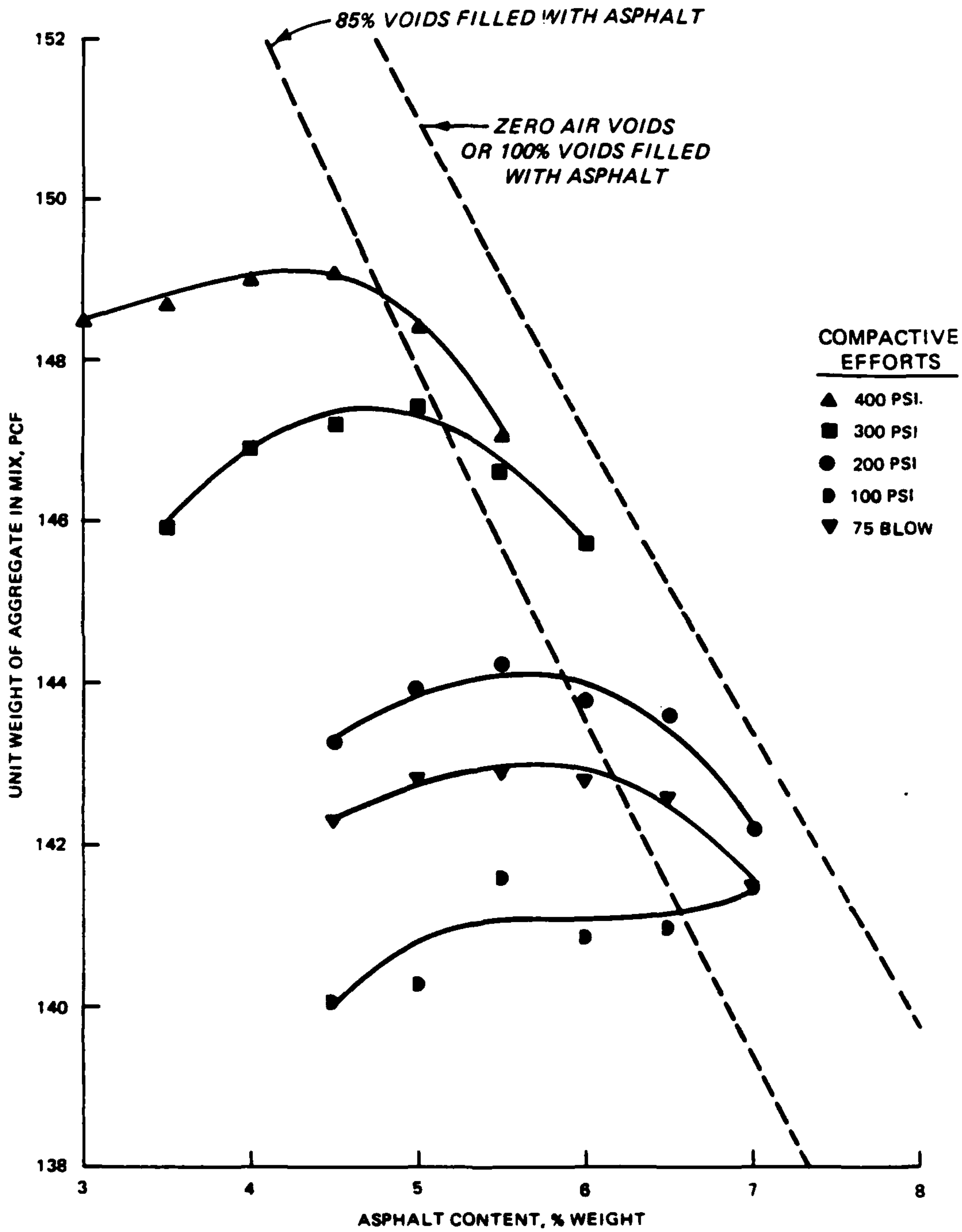

Figure 20. Compaction Curves, 3/4-Inch and AC 40 Mixes.

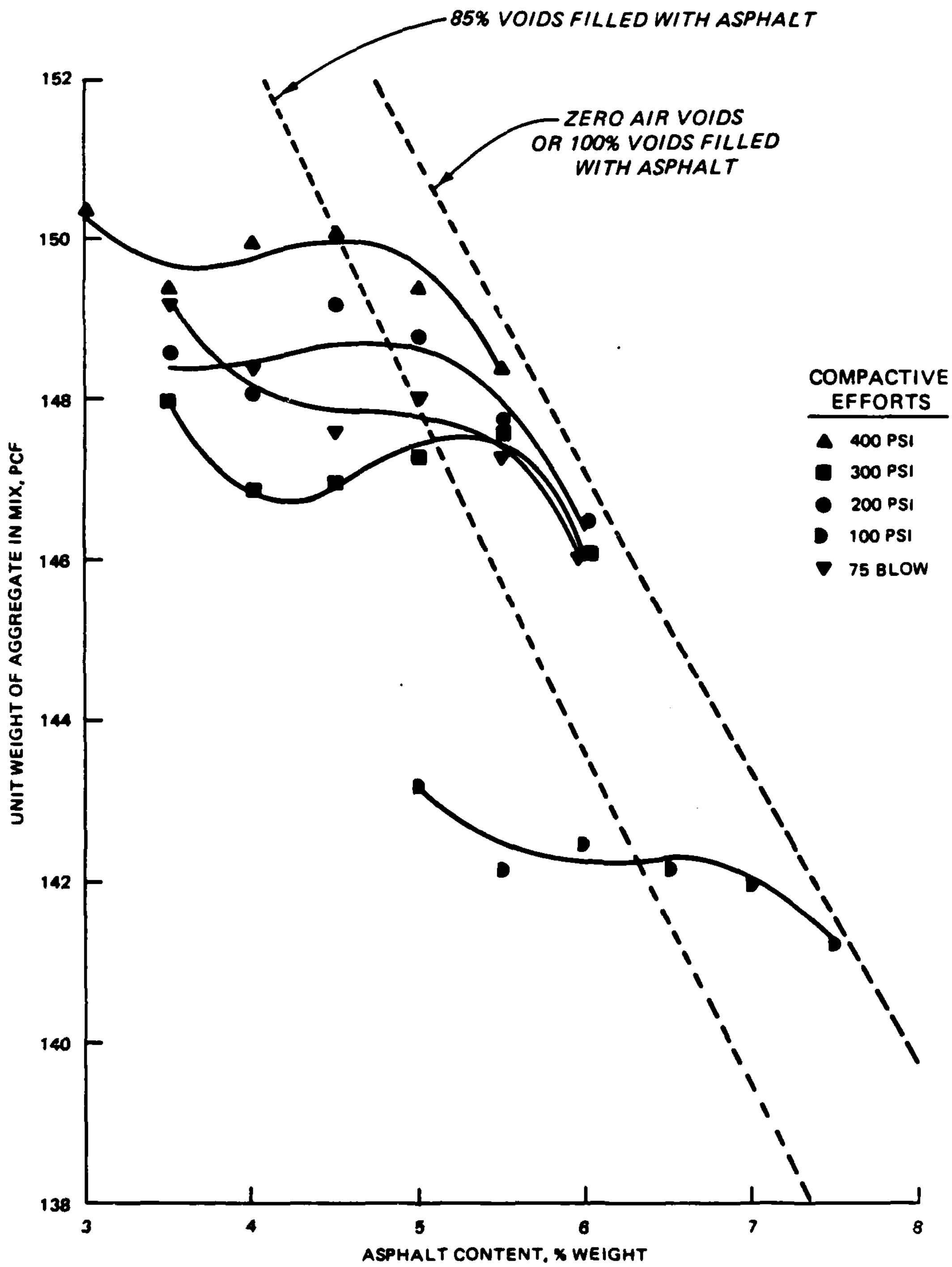

Figure 21. Compaction Curves, 1-Inch and AC 40 Mixes.

TABLE 10. COMPARISON OF OPTIMUM ASPHALT CONTENTS.

Mix	Compactive effort	Optimum, percent by weight: Heavy-duty mix criteria	Optimum, percent by weight: Maximum asphalt content mix with GSI = 1[a]
3/4-inch aggregate and AC 20	400 psi	4.6	4.5
	300 psi	4.6	4.5
	200 psi	4.9	5.0
	100 psi	5.7	6.5
	75 blow	5.2	---
3/4-inch aggregate and AC 40	400 psi	4.1	4.0
	300 psi	4.5	4.5
	200 psi	5.3	5.5
	100 psi	6.0	6.5
	75 blow	5.5	---
1-inch aggregate and AC 20	400 psi	4.0	5.0
	300 psi	3.8	4.0
	200 psi	4.0	4.5
	100 psi	5.0	5.0
	75 blow	4.2	---
1-inch aggregate and AC 40	400 psi	4.0	4.5
	300 psi	4.5	5.0
	200 psi	4.2	5.0
	100 psi	5.7	7.0
	75 Blow	4.5	---

[a]GSI is taken from the gyratory compactor and used as an indicator of mix stability during compaction.

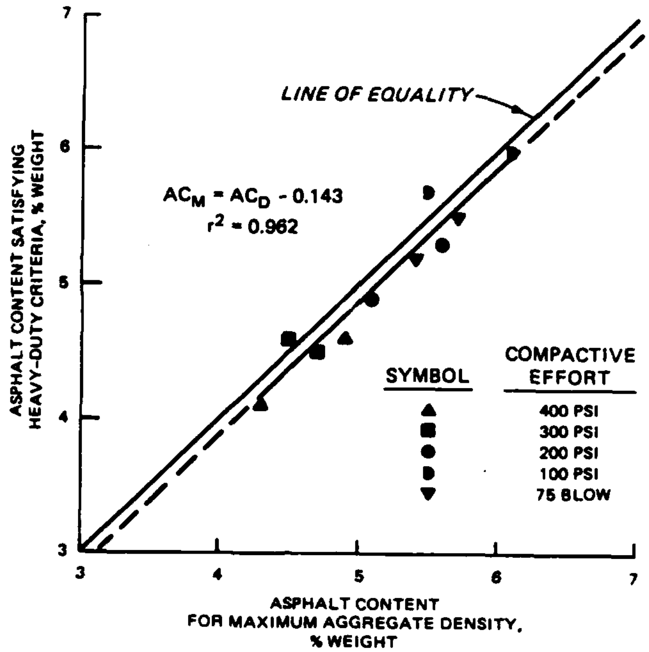

Figure 22. Comparison of Optimum Asphalt Contents, 3/4-Inch Maximum-Sized Aggregate Mixes.

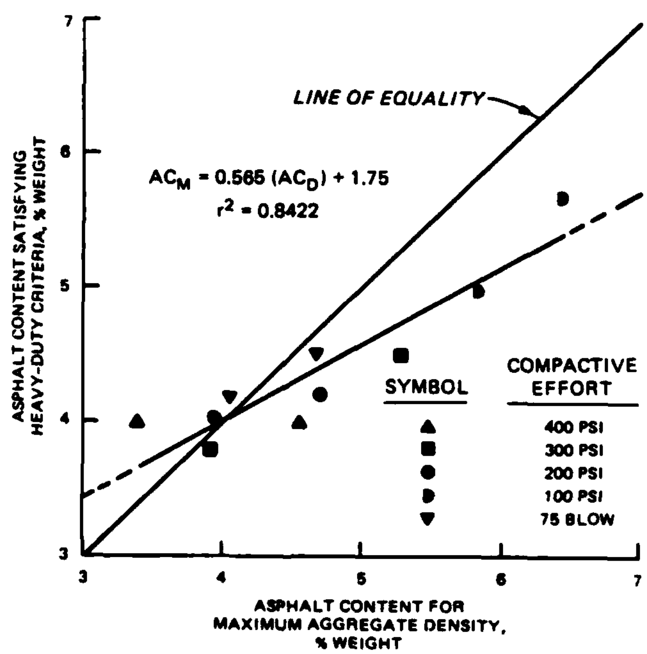

Figure 23. Comparison of Optimum Asphalt Contents, 1-Inch Maximum-Sized Aggregate Mixes.

These figures show a difference in required asphalt content that apparently is a result of aggregate gradation. Figures 18-21 also show that mixes made with the coarser gradation have flatter density-asphalt content curves; they are similar to those of free-draining gravels and sands. Low surface-area-to-volume ratios of the coarser mixes allow them to be compacted to higher densities at lower asphalt contents than finer mixes. A lesser amount of asphalt is required to coat and lubricate the coarser 1-inch aggregate mixes.

To infer mix behavior from preceding preliminary data, assume that a 3/4-inch aggregate and AC 20 mix designed using heavy-duty criteria and 75-blow compactive effort is to be constructed and trafficked with 400 psi contact pressure traffic. The asphalt content of a mix that satisfies requirements of the heavy-duty criteria (Table 6) is determined first. Then, other weight-volume properties are approximated by interpolating curves of total density, air voids, voids in mineral aggregate, and voids filled with asphalt plotted as functions of asphalt content. Each value is found at the indicated optimum asphalt content. The following is selected as a satisfactory asphalt concrete mix for construction.

Asphalt content: 5.2 percent AC 20
Total mix density: 152.2 pcf
Volume of asphalt (percent of total volume): 12.3
Volume of air voids (percent of total volume): 3.9
Voids in aggregate matrix (percent of total volume): 16.2
Asphalt-filled voids (percent voids in aggregate matrix): 76.0

If this compacted mix is trafficked by aircraft with 400 psi pressures, it is assumed that its properties would, as a result of traffic, approach those of the gyratory specimens compacted at 400 psi at the same asphalt content. This assumption is based on the B-52 and T-38 studies (References 13 and 14). Therefore, after traffic simulation, the mix properties are:

Total mix density: 155.4 pcf
Volume of asphalt (percent of total volume): 12.5
Volume of air voids (percent of total volume): 1.9
Voids in aggregate matrix (percent of total volume): 14.4
Asphalt-filled voids (percent voids in aggregate matrix): 87.2
GSI value: approximately 1.3; <u>indicates instability</u>

If the 400 psi gyratory compaction is analogous to 400 psi tire traffic, this analysis indicates that a 5.2-percent mix would densify under traffic a total of about 2 percent. Its constant asphalt volume would fill more of the voids, as expected. The gyratory stability index indicates that the mix would become unstable when subjected to some unknown volume of 400 psi traffic. Rutting and other plastic movements would probably occur during traffic. It is not possible from this laboratory data to estimate the volume of traffic to cause plastic or rutting failure of a surface mixture constructed to the preceding specifications.

The above assumptions and analyses lead to the position that the use of both the current heavy-duty criteria and current field compactive effort (equivalent to 75-blow laboratory compaction) is <u>not</u> recommended to design mixes that will resist aircraft contact pressures in the 400 psi range; instability and rutting occur. Some type of modification has to be made either to the mix selection criteria or to the compactive effort applied during design and construction. Higher initial densities and lower asphalt contents are indicated for mixes to remain stable and resist rutting at these high contact pressures.

B. SUPPLEMENTAL NONCONVENTIONAL TESTING: UNMODIFIED ASPHALT CEMENT MIXES

Table 11 shows average properties of mixes made with unmodified asphalt cements AC 20 and AC 40. The mixes were produced at the previously used compactive efforts with the same aggregates and gradations. Three asphalt contents (1/2 percent less, estimated optimum, and 1/2 percent greater, by weight) were used with 3/4-inch aggregate mixes. The 1-inch aggregate mixes were produced at the estimated optimum. The average properties of groups of 14 specimens are given in this table; 14 specimens were made at each asphalt content. These specimens were made for studying mix properties that cannot be evaluated by use of Marshall stability and flow tests.

1. Modulus Behavior

Table 12 presents average moduli from static and resilient indirect tensile testing at 77 and 100 °F. Static testing was performed by loading specimens to failure by splitting. Resilient testing was nondestructive. Specimens were repeatedly loaded and unloaded. The total resilient modulus is based on the mix's response to loading, and the instantaneous resilient modulus is based on the response to unloading.

Analyses of variance and Fisher's least significant difference tests (Reference 23) were performed on data from this table at the optimum asphalt contents for each aggregate-asphalt combination and compactive effort. Two-way analyses of variance were performed with type of mix (asphalt-aggregate combination) and compactive efforts as variables. Specific findings are given in Table 13. Generally, mixes made with 3/4-inch aggregates and AC 20 asphalt and compacted with efforts greater than 100 psi produced the highest moduli at 77 °F. At 100 °F, moduli differences between mixes became less significant; however, mixes made at the lowest (100 psi) compactive effort maintained the lowest ranking.

Test data indicated that the resilient indirect tensile test was more sensitive to differences in moduli at 77 °F.

2. Strength Behavior

Strength of asphalt mixes was studied at two levels. The lower level was concerned with the tensile behavior, and the higher level involved the shear strength measured with the direct shear apparatus.

a. Tensile Behavior

Tensile strength data from indirect tensile testing are given in Table 14. Observation of tensile strengths with 3/4-inch aggregate indicates

TABLE 11. AVERAGE SPECIMEN PROPERTIES[a] FOR SUPPLEMENTAL TESTING.

Mix	Compactive effort	Asphalt content % weight	Total mix density pcf	Asphalt content % volume	Voids in matrix % volume	Air voids % volume	Voids filled %
3/4-inch aggregate and AC 20	400 psi	4.1	152.6	9.7	14.9	5.2	65.0
		4.6	153.6	11.0	14.8	3.8	74.0
		5.1	154.6	12.2	14.7	2.5	83.1
	300 psi	4.1	152.3	9.7	15.1	5.4	64.1
		4.6	153.1	10.9	15.1	4.2	72.2
		5.1	154.1	12.2	15.0	2.8	81.1
	200 psi	4.4	152.4	10.4	15.4	4.9	67.8
		4.9	154.3	11.7	14.8	3.0	79.5
		5.4	155.1	13.0	14.7	1.8	88.2
	100 psi	5.2	151.3	12.2	16.6	4.4	73.5
		5.7	152.0	13.4	16.8	3.3	80.3
		6.2	152.9	14.7	16.7	2.0	88.3
	75 blow	4.7	151.2	11.0	16.3	5.3	67.6
		5.2	152.0	12.3	16.3	4.0	75.7
		5.7	152.2	13.5	16.6	3.2	81.0
3/4-inch aggregate and AC 40	400 psi	3.6	151.6	8.4	15.0	6.6	55.9
		4.1	152.9	9.7	14.8	5.1	65.2
		4.6	154.0	10.9	14.6	3.7	74.6
	300 psi	4.0	149.1	9.2	16.8	7.6	54.7
		4.5	150.3	10.4	16.6	6.2	62.7
		5.0	151.2	11.7	16.5	4.8	70.7
	200 psi	4.8	149.6	11.1	17.2	6.2	64.2
		5.3	150.9	12.3	17.0	4.6	72.6
		5.8	151.7	13.5	16.9	3.4	79.8

[a]Each property is the average of 14 specimens.

TABLE 11. AVERAGE SPECIMEN PROPERTIES[a] FOR SUPPLEMENTAL TESTING (CONCLUDED).

Mix	Compactive effort	Asphalt content % weight	Total mix density pcf	Asphalt content % volume	Voids in matrix % volume	Air voids % volume	Voids filled %
3/4-inch aggregate and AC 40 (Continued)	100 psi	5.5	147.2	12.5	19.2	6.7	65.0
		6.0	148.6	13.7	18.8	5.1	72.9
		6.5	149.4	15.0	18.8	3.8	79.6
	75 blow	5.0	148.9	11.5	17.8	6.3	64.6
		5.5	149.6	12.7	17.8	5.1	71.2
		6.0	150.9	14.0	17.6	3.6	79.4
1-inch aggregate and AC 20	400 psi	4.1	156.7	10.0	12.7	2.7	78.5
	300 psi	3.8	154.9	9.1	13.4	4.3	68.4
	200 psi	4.0	154.1	9.6	14.1	4.5	68.1
	100 psi	5.0	152.2	11.8	15.9	4.1	74.0
	75 blow	4.4	154.0	10.4	14.4	4.0	72.4
1-inch aggregate and AC 40	400 psi	3.9	154.9	9.3	13.5	4.2	68.9
	300 psi	4.5	155.1	10.8	13.9	3.2	77.1
	200 psi	4.3	152.5	10.1	15.2	5.1	66.6
	100 psi	5.7	152.7	13.4	16.3	2.9	82.1
	75 blow	4.5	153.4	10.6	14.9	4.3	71.4

TABLE 12. INDIRECT TENSILE DATA SUMMARY, MODULI.

Mix	Compactive effort	Asphalt content % weight	Average resilient elastic modulus at 77 °F, psi[a]		Average resilient elastic modulus at 100 °F, psi[a]		Average static elastic modulus psi[b]	
			Instantaneous	Total	Instantaneous	Total	77 °F	100 °F
3/4-inch aggregate and AC 20	400 psi	4.1	141,570	111,160	94,630	66,480	70,830	26,710
		4.6	148,970	122,100	99,690	63,840	64,980	30,330
		5.1	154,120	116,970	101,400	64,720	52,860	35,480
	300 psi	4.1	156,230	117,050	---	---	63,670	30,450
		4.6	160,360	122,990	95,960	62,180	57,970	29,790
		5.1	157,330	115,790	94,080	61,530	45,110	41,930
	200 psi	4.4	151,480	114,230	107,280	72,270	36,890	41,530
		4.9	154,370	121,340	107,650	73,760	40,230	42,890
		5.4	159,200	118,480	103,640	64,070	34,880	29,560
	100 psi	5.2	163,900	113,940	70,400	46,390	34,700	21,720
		5.7	145,890	105,610	62,530	42,120	33,500	22,870
		6.2	134,430	99,480	58,180	44,890	28,290	20,930
	75 blows	4.7	152,630	103,630	73,730	52,380	49,060	47,950
		5.2	144,790	102,300	72,040	49,850	46,790	42,250
		5.7	145,890	108,260	72,480	51,850	38,390	34,690
3/4-inch aggregate and AC 40	400 psi	3.6	154,940	111,960	109,700	71,040	68,220	47,550
		4.1	150,970	105,850	101,650	63,080	66,700	44,090
		4.6	151,000	107,860	94,140	66,950	68,130	40,530
	300 psi	4.0	142,500	98,250	90,300	58,560	58,950	31,680
		4.5	140,610	98,560	84,730	57,890	49,560	39,140
		5.0	146,200	103,950	92,570	61,720	48,440	33,880

[a]Average of six tests (two tests each on three specimens).

[b]Average of three tests (one test on three specimens).

TABLE 12. INDIRECT TENSILE DATA SUMMARY, MODULI (CONCLUDED).

Mix	Compactive effort	Asphalt content % weight	Average resilient elastic modulus at 77 °F, psi		Average resilient elastic modulus at 100 °F, psi		Average static elastic modulus psi	
			Instantaneous	Total	Instantaneous	Total	77 °F	100 °F
3/4-inch aggregate and AC 40 (Continued)	200 psi	4.8	127,850	92,460	65,800	44,650	39,320	43,700
		5.3	139,180	93,670	81,740	52,900	43,680	31,040
		5.8	138,240	99,800	81,940	54,640	40,300	28,040
	100 psi	5.5	133,660	96,180	64,830	45,730	36,730	20,420
		6.0	128,760	90,970	72,520	45,080	32,460	25,900
		6.5	131,580	89,820	69,060	43,730	34,060	30,900
	75 blows	5.0	134,270	97,500	80,590	56,360	49,410	44,720
		5.5	137,240	99,440	87,100	60,470	49,740	35,600
		6.0	138,350	96,280	75,060	53,760	46,240	36,040
1-inch aggregate and AC 20	400 psi	4.1	141,730	101,310	91,130	63,930	60,570	44,030
	300 psi	3.8	152,180	105,760	105,300	70,690	52,220	38,490
	200 psi	4.0	143,440	93,680	93,710	63,070	48,850	27,530
	100 psi	5.0	120,040	90,680	91,300	60,870	35,690	17,560
	75 blows	4.4	143,670	103,800	90,300	58,200	59,850	32,220
1-inch aggregate and AC 40	400 psi	3.9	133,050	91,680	89,180	67,650	62,720	45,000
	300 psi	4.5	130,910	86,880	86,950	62,250	57,750	45,530
	200 psi	4.3	119,210	87,790	107,140	74,600	51,680	31,660
	100 psi	5.7	119,010	85,240	81,280	56,210	36,210	21,050
	75 blows	4.5	138,360	98,940	104,100	69,060	46,570	34,160

TABLE 13. SUMMARY OF MODULUS FINDINGS AT OPTIMUM ASPHALT CONTENTS[a]

Type of modulus	Temperature, °F	Findings
Instantaneous	77	3/4-inch and AC 20 mixes produced the highest average moduli.
		1-inch and AC 40 mixes produced the lowest average moduli.
		100 psi gyratory efforts produced significantly lower average moduli than mixes compacted to higher efforts.
	100	No significant difference in moduli was found because of either mix or compactive effort.
Total	77	AC 20 mixes (with either gradation) produced significantly higher average moduli.
		1-inch and AC 40 mixes produced the lowest moduli.
		No significant difference in moduli was found as a result of compactive effort.
	100	No significant difference because of mix.
		100 psi gyratory efforts produced significantly lower average moduli than mixes compacted to higher efforts.
Static	77	No significant difference in moduli was found because of mix.
		400 psi gyratory efforts produced significantly higher average moduli.
		100 psi gyratory efforts produced significantly lower average moduli.
	100	No significant difference in moduli was found because of mix.
		100 psi gyratory efforts produced significantly lower average moduli than mixes compacted to higher efforts.

[a]Optimums satisfy heavy-duty mix criteria of Table 6.

TABLE 14. INDIRECT TENSILE STRENGTH[a] SUMMARY.

Mix	Compactive effort	Asphalt content % weight	Tensile strength psi 77 °F	Tensile strength psi 100 °F
3/4-inch aggregate and AC 20	400 psi	4.1	173	64
		4.6	158	61
		5.1	142	55
	300 psi	4.1	153	63
		4.6	146	63
		5.1	122	67
	200 psi	4.4	131	66
		4.9	126	60
		5.4	115	47
	100 psi	5.2	121	45
		5.7	113	46
		6.2	107	45
	75 blow	4.7	129	75
		5.2	149	63
		5.7	129	62
3/4-inch aggregate and AC 40	400 psi	3.6	157	72
		4.1	162	73
		4.6	172	73
	300 psi	4.0	135	56
		4.5	142	64
		5.0	139	66
	200 psi	4.8	135	59
		5.3	128	62
		5.8	123	52
	100 psi	5.5	102	49
		6.0	115	51
		6.5	119	60
	75 blow	5.0	125	71
		5.5	123	66
		6.0	130	67

[a]Each entry is the average of three static indirect tensile tests.

TABLE 14. INDIRECT TENSILE STRENGTH[a] SUMMARY (CONCLUDED).

Mix	Compactive effort	Asphalt content % weight	Tensile strength psi 77 °F	Tensile strength psi 100 °F
1-inch aggregate and AC 20	400 psi	4.1	145	70
	300 psi	3.8	141	71
	200 psi	4.0	127	54
	100 psi	5.0	109	38
	75 blow	4.4	125	59
1-inch aggregate and AC 40	400 psi	3.9	151	81
	300 psi	4.5	140	81
	200 psi	4.3	124	62
	100 psi	5.7	94	50
	75 blow	4.5	133	72

different trends with each asphalt type. AC 20 mixes showed decreasing tensile strengths with increased asphalt contents, whereas AC 40 mixes showed either almost constant values or mixed trends. This indicates that the more viscous AC 40 grade is better for providing consistent high tensile strength.

Figure 24 shows a relationship developed from tensile strength data from Table 14. Based on 64 data entries from all the gyratory-compacted specimens, the regression shows that mix tensile strength is primarily a function of compactive effort and temperature with asphalt content having a lesser effect. The relationship suggests that mixes designed to meet heavy-duty criteria would possess higher tensile strengths when higher compactive efforts are required.

b. Direct Shear Behavior

Results of direct shear testing are given in Table 15; testing was done at 77 °F. Data shown are usually averaged from three tests. As expected, shear stresses on the failure plane increased with the level of applied normal stress. Shear strengths given in Table 15 are from forces required to move aggregate particles relative to each other along the failure surface. The applied forces generate crushing and shearing of aggregates and move particles up and over each other. In some cases, deformations amounting to about 11 percent of specimen diameter (up to about 0.44 inch) were needed to develop maximum shear loads.

Analyses of variance and least-significant-difference techniques indicated that 3/4-inch gradation mixes compacted at the 75-blow hammer and the 100 psi gyratory efforts were consistently lower in strength than those compacted at 200, 300, and 400 psi stress levels in the gyratory compactor. The 200-400 psi compacted mixes were tighter and more physically stable. The 300 psi gyratory effort consistently produced mixes with the highest shear strengths.

The data indicate that, at similar asphalt contents, mixes compacted to higher efforts (200-400 psi) with more viscous AC 40 asphalt cement developed higher shear strengths that were independent of gradation.

c. Combined Tensile - Direct Shear Behavior

Indirect tensile strengths and direct shear data from Tables 14 and 15 were combined and used to define mix behavior at 77 °F in terms of friction and cohesion. The analysis implicitly assumes that the tensile strength determined with the indirect tensile test is identical to that found in a uniaxial tension test. Tensile strengths were plotted as points on the normal stress or X-axis, and direct shear results were plotted as combined stresses on both axes. The best-fit line through these points defined mix behavior.

Typical values of friction and cohesion are given in Table 16. Figures 25-28 show the combined strength envelopes of mixes at optimum asphalt contents. Friction angles ranged from 55 to 74 degrees and were generally independent of asphalt content.

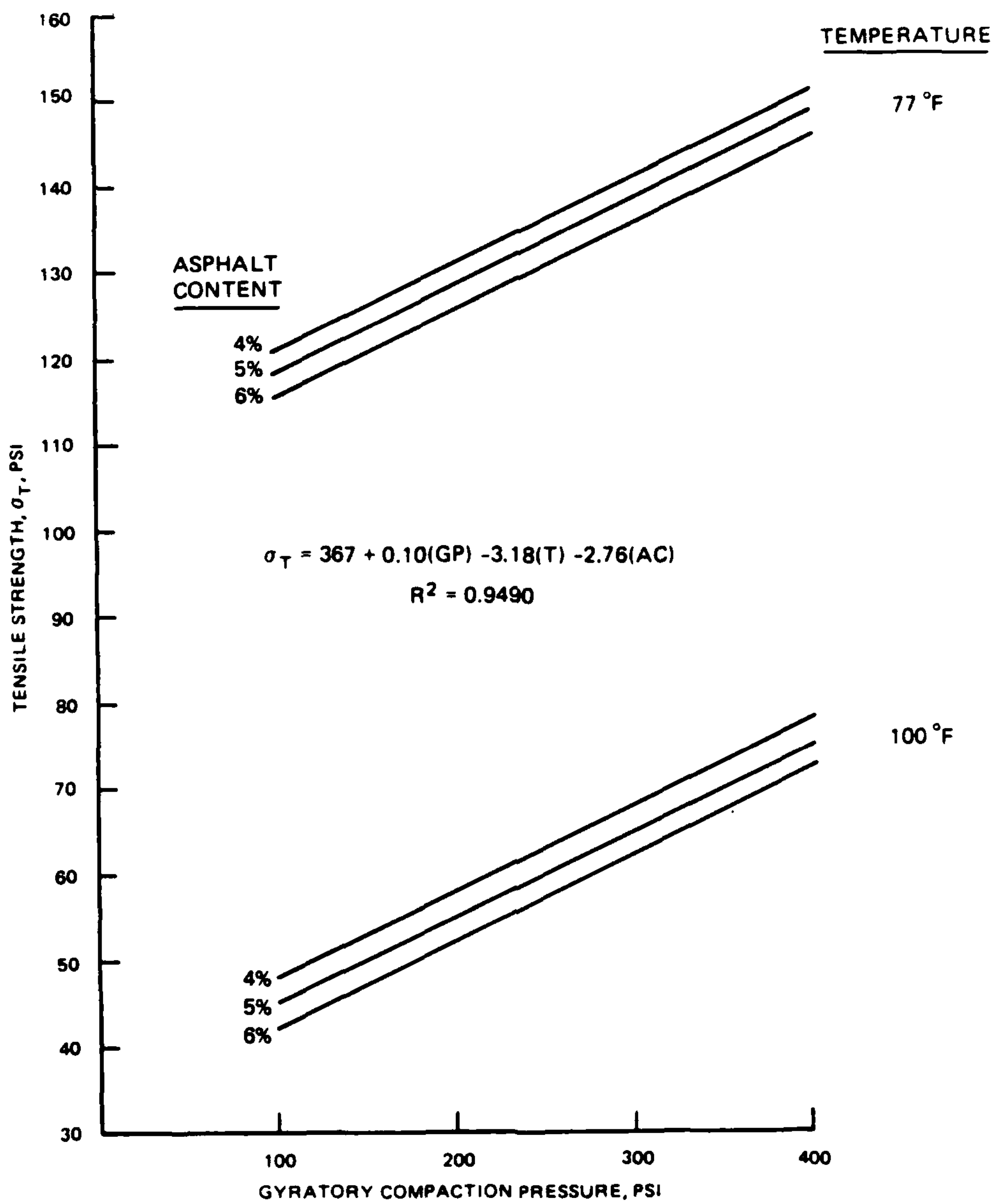

Figure 24. General Tensile Strength Relationship for Gyratory-Compacted Mixes.

TABLE 15. DIRECT SHEAR DATA SUMMARY, 77 °F.

Mix	Compactive effort	Asphalt content % weight	Normal stress psi	Average results[a] Shear strength psi	Deformation % diameter
3/4-inch aggregate and AC 20	400 psi	4.1	100	456.2	4.93
			200	594.2	4.29
		4.6	100	466.9	4.26
			200	580.9	4.42
		5.1	100	413.8	4.22
			200	588.2	4.48
	300 psi	4.1	100	451.6	3.69
			200	631.3	4.87
		4.6	100	447.6	4.00
			200	595.5	4.40
		5.1	100	408.5	4.53
			200	582.2	4.58
	200 psi	4.4	100	431.0	5.56
			200	616.7	5.40
		4.9	100	404.5	4.98
			200	610.1	5.80
		5.4	100	392.6	5.03
			200	559.7	7.04
	100 psi	5.2	100	397.9	5.78
			200	555.7	6.86
		5.7	100	391.3	5.94
			200	559.7	6.19
		6.2	100	367.4	6.51
			200	558.4	7.88
	75 blow	4.7	100	368.7	4.37
			200	498.7	5.90
		5.2	100	371.4	3.90
			200	509.3	5.44
		5.7	100	360.8	4.90
			200	478.8	6.82

[a]Averaged for three tests in most cases.

TABLE 15. DIRECT SHEAR DATA SUMMARY, 77 °F (CONTINUED).

Mix	Compactive effort	Asphalt content % weight	Normal stress psi	Average results: Shear strength psi	Average results: Deformation % diameter
3/4-inch aggregate and AC 40	400 psi	3.6	100	407.2	5.43
			200	954.9	6.93
		4.1	100	399.2	6.76
			200	1,153.2	7.47
		4.6	100	343.5	5.92
			200	1,168.4	8.25
	300 psi	4.0	100	439.0	6.61
			200	1,269.3	8.14
		4.5	100	449.6	6.36
			200	1,115.4	7.92
		5.0	100	378.0	6.33
			200	986.8	7.46
	200 psi	4.8	100	378.0	6.12
			200	984.1	7.53
		5.3	100	395.2	6.41
			200	1,086.2	8.00
		5.8	100	371.4	7.41
			200	1,078.3	8.34
	100 psi	5.5	100	354.1	5.33
			200	527.9	6.53
		6.0	100	323.6	6.04
			200	521.2	6.98
		6.5	100	372.7	6.05
			200	518.6	6.92
	75 blow	5.0	100	338.2	4.78
			200	466.9	5.45
		5.5	100	340.9	4.70
			200	461.5	5.67
		6.0	100	359.4	5.22
			200	453.6	5.06
1-inch aggregate and AC 20	400 psi	4.1	100	---	---
			200	724.2	5.76
	300 psi	3.8	100	467.4	4.37
			200	633.8	5.42
	200 psi	4.0	100	472.0	4.32
			200	664.5	6.13

TABLE 15. DIRECT SHEAR DATA SUMMARY, 77 °F (CONCLUDED).

Mix	Compactive effort	Asphalt content % weight	Normal stress psi	Average results: Shear strength psi	Average results: Deformation % diameter
1-inch aggregate and AC 20 (continued)	100 psi	5.0	100	404.1	9.16
			200	559.5	7.56
	75 blow	4.4	100	---	---
			200	635.1	6.23
1-inch aggregate and AC 40	400 psi	3.9	100	508.0	5.61
			200	801.1	9.78
		4.1	100	509.2	4.02
			200	760.5	6.46
	300 psi	3.8	100	515.0	4.40
			200	867.1	8.61
		4.5	100	527.2	5.73
			200	823.6	8.43
	200 psi	4.0	100	499.9	3.96
			200	922.8	10.7
		4.3	100	500.0	6.28
			200	754.6	7.93
	100 psi	5.0	100	524.5	8.91
			200	747.8	10.5
		5.7	100	521.2	7.30
			200	725.5	8.38
	75 blow	4.5	100	380.6	6.44
			200	530.5	5.63

TABLE 16. COMBINED STRENGTH REGRESSION RESULTS[a] AT 77 °F.

Mix	Compactive effort	Asphalt content % weight	Cohesion psi	Friction angle degrees
3/4-inch aggregate and AC 20	400 psi	4.1	282	58
		4.6	270	59
		5.1	243	60
	300 psi	4.1	273	61
		4.6	258	60
		5.1	223	61
	200 psi	4.4	244	62
		4.9	230	62
		5.4	207	61
	100 psi	5.2	214	60
		5.7	205	61
		6.2	192	61
	75 blow	4.7	202	57
		5.2	220	56
		5.7	196	56
3/4-inch aggregate and AC 40	400 psi	3.6	337	68
		4.1	386	71
		4.6	387	70
	300 psi	4.0	380	74
		4.5	364	72
		5.0	312	70
	200 psi	4.8	306	70
		5.3	320	72
		5.8	303	72
	100 psi	5.5	179	60
		6.0	181	59
		6.5	198	59
	75 blow	5.0	184	55
		5.5	182	55
		6.0	191	55

[a]Three points were used to compute cohesion and friction values; tensile strength and shear strengths at normal stresses (from Tables 14 and 15).

TABLE 16. COMBINED STRENGTH REGRESSION RESULTS[a] AT 77 °F (CONCLUDED).

Mix	Compactive effort	Asphalt content % weight	Cohesion psi	Friction angle degrees
1-inch aggregate and AC 20	400 psi	4.1	304	65
	300 psi	3.8	268	62
	200 psi	4.0	261	64
	100 psi	5.0	205	61
	75 blow	4.4	244	63
1-inch aggregate and AC 40	400 psi	3.9	326	66
	300 psi	4.5	323	67
	200 psi	4.3	283	67
	100 psi	5.7	244	68
	75 blow	4.5	215	58

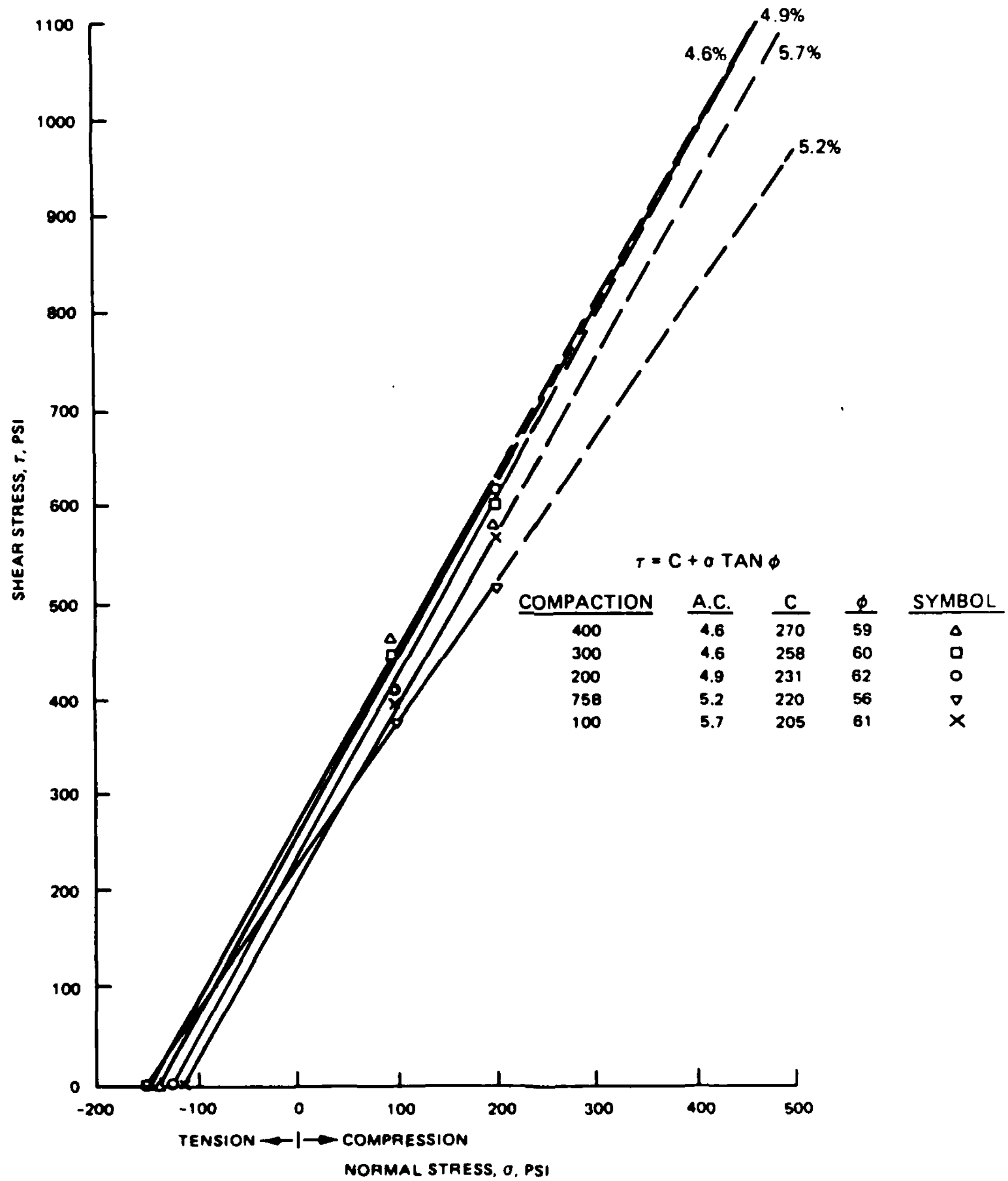

Figure 25. Combined Strength Envelope, 3/4-Inch and AC 20 Mixes at Optimum Asphalt Contents.

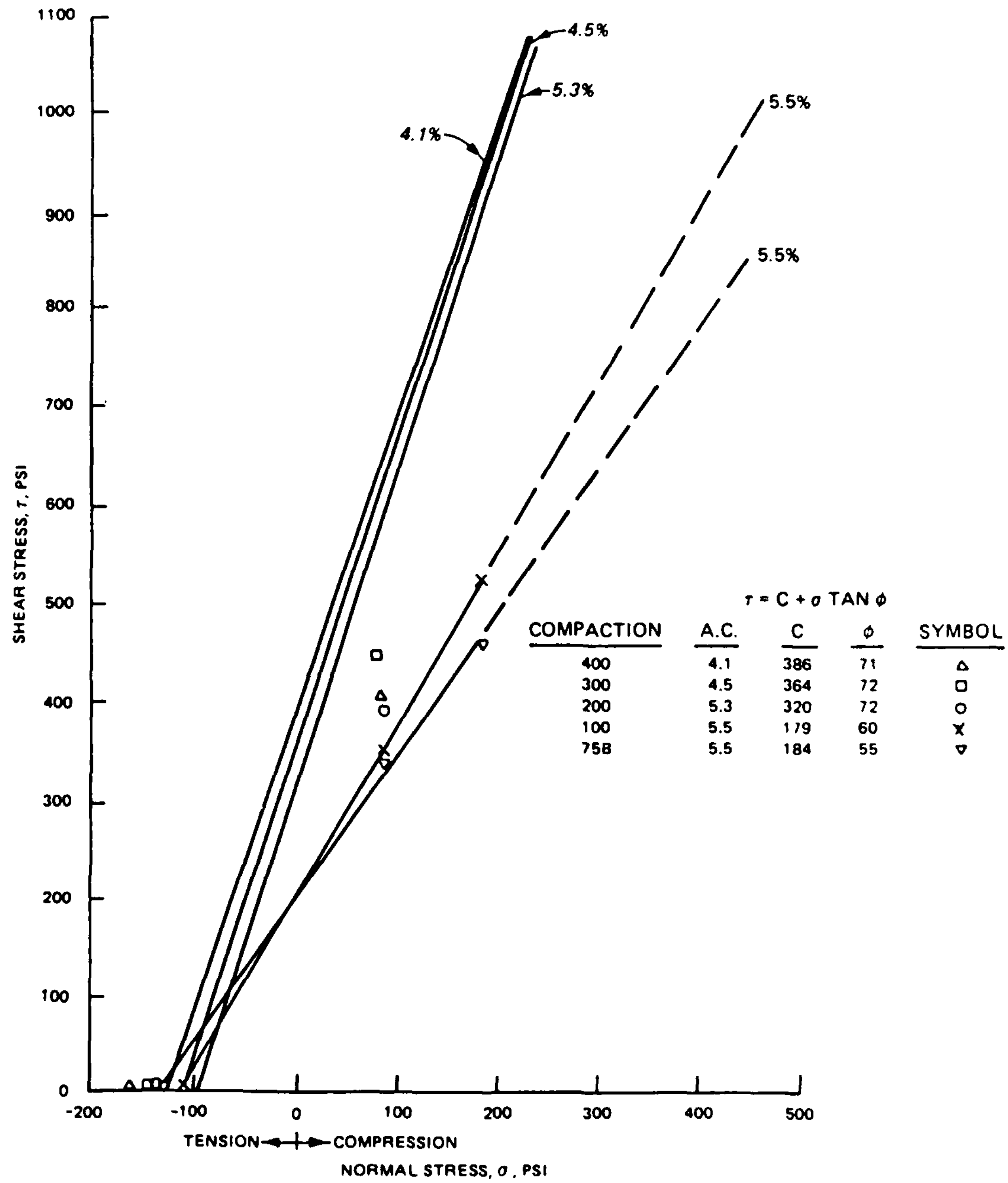

Figure 26. Combined Strength Envelope, 3/4-Inch and AC 40 Mixes at Optimum Asphalt Contents.

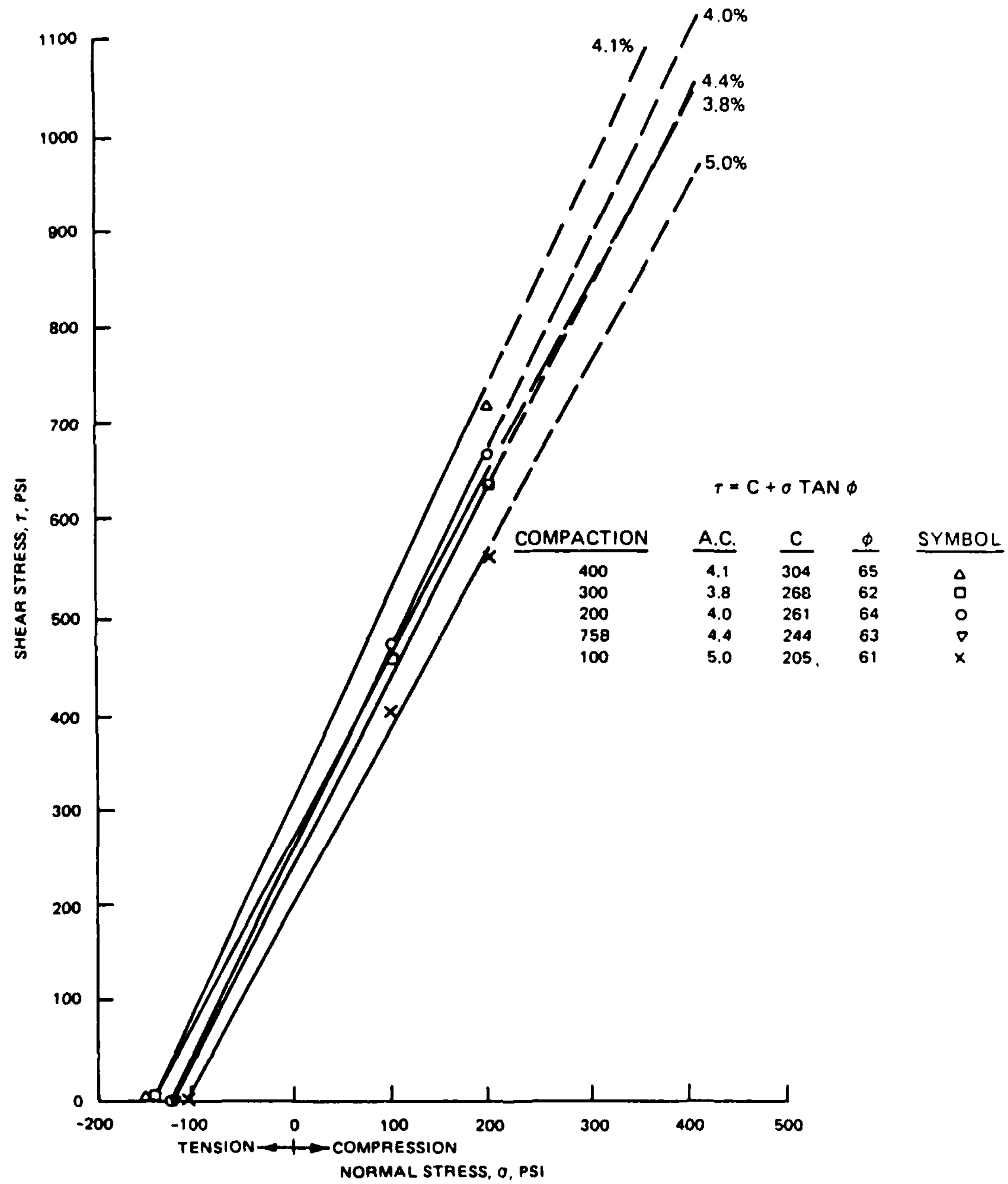

Figure 27. Combined Strength Envelope, 1-Inch and AC 20 Mixes at Optimum Asphalt Contents.

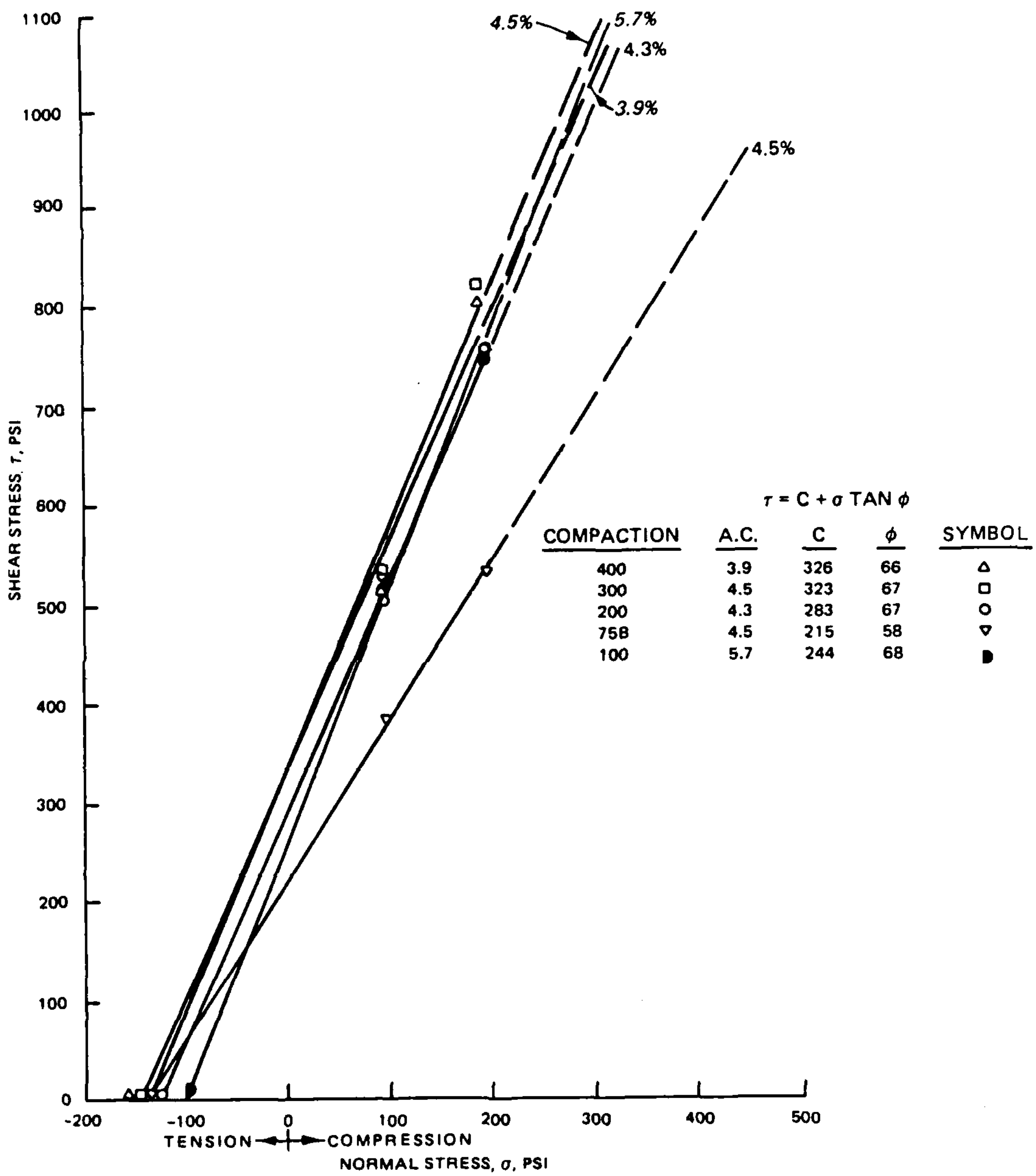

Figure 28. Combined Strength Envelope, 1-Inch and AC 40 Mixes at Optimum Asphalt Contents.

Figures 29 and 30 show the effects of gradation, compaction, and asphalt grade on the cohesion of mixes. The lines drawn on the figures are best-fit relationships between cohesion and voids in the mineral aggregate. Trends in the data show that the coarser 1-inch gradation allowed the mixes to be compacted into tighter configurations. The effect of increased compactive effort can be seen as increasing values of cohesion and decreasing voids in the mineral aggregate. From these results, the 3/4-inch gradation and AC 40 asphalt mixes had the highest strengths at 77 °F.

3. Asphalt-Aging Behavior

Tables 17 and 18 give results of accelerated asphalt-aging tests performed on all mixes. These mixes were subjected to 225 °F temperatures for 7 days.

Two-way analyses of variance, comparing all compactive efforts and levels of asphalt content (heavy-duty optimum, 1/2 percent lean of optimum, and 1/2 percent rich of optimum), were conducted. Least significant differences were also computed at the 95-percent level. The following conclusions were reached.

a. 3/4-Inch and AC 20 Mixes

(1) Levels of compactive effort did not significantly affect durability indices of the mixes.

(2) Mixes that were made on the rich side of optimum had significantly higher durability indices than those at optimum or slightly lean of optimum.

b. 3/4-Inch and AC 40 Mixes

(1) There were no significant differences between mean durability indices in either terms of levels of compactive effort or level of asphalt content. This means that the range of asphalt contents investigated did not provide enough differenc' in durability index to definitely select a best mix for long-range mix durability.

(2) The data could also imply that penetration results are not as dependable or consistent with harder asphalts after laboratory extraction and recovery procedures.

A regression was performed on data from mixes made with AC 20 asphalt and 3/4-inch gradation. Figure 31 shows that the resistance to age-hardening, expressed as durability index, is a function of the volume of air voids within the mixes. These results illustrate that age resistance depends on the volume of mix that is permeable to air or water (this volume can be called effective porosity). The figure shows that the resistance to aging increases as the effective porosity decreases. This suggests that mixes having high asphalt contents are best for resisting the effects of aging.

It is reasonable to assume that mixes made with the more viscous AC 40 asphalt are similarly affected by aging. Results of this study did not

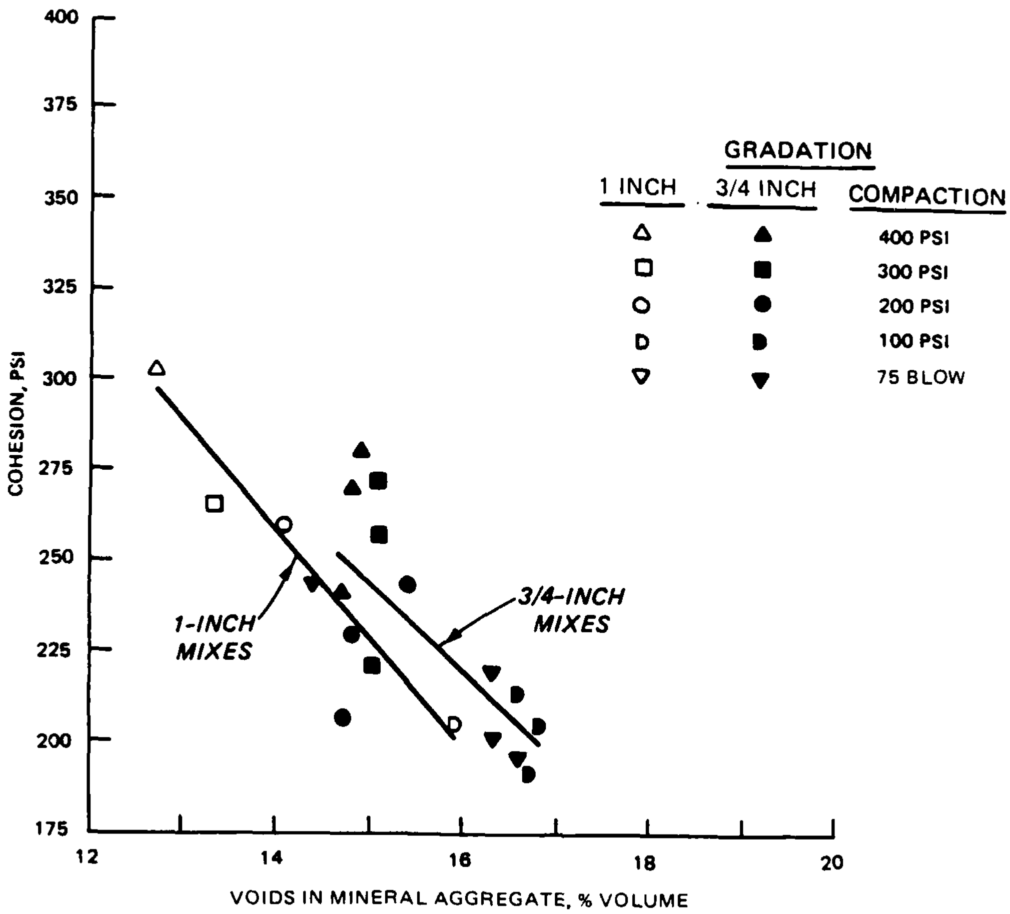

Figure 29. Cohesion of AC 20 Mixes.

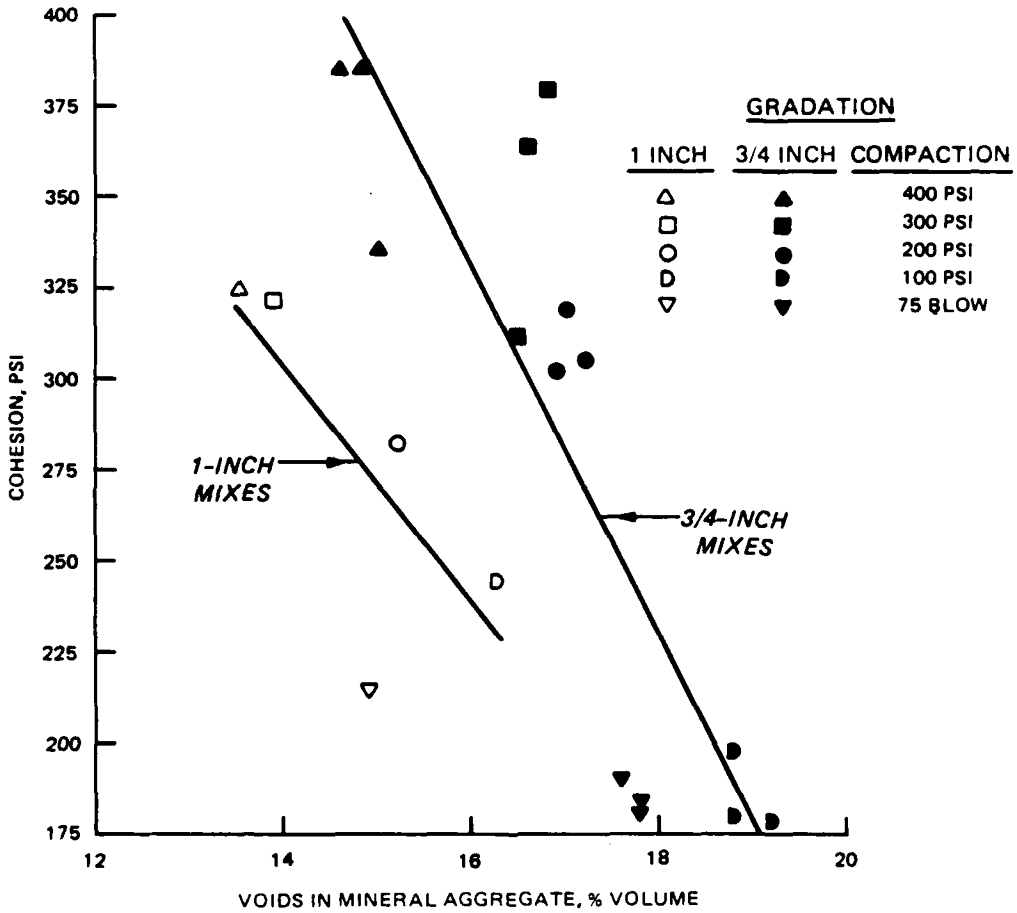

Figure 30. Cohesion of AC 40 Mixes.

TABLE 17. ACCELERATED AGING TEST RESULTS FOR AC 20 MIXES.

Aggregate	Compactive effort	Asphalt content % weight	After aging: Penetration P_{age}	After aging: Durability index[a]
3/4 inch	400 psi	4.1	24	0.32
		4.6	30	0.40
		5.1	29	0.39
	300 psi	4.1	24	0.32
		4.6	23	0.31
		5.1	29	0.39
	200 psi	4.4	22	0.29
		4.9	25	0.33
		5.4	35	0.47
	100 psi	5.2	23	0.31
		5.7	23	0.31
		6.2	36	0.48
	75 blow	4.7	20	0.27
		5.2	21	0.28
		5.7	20	0.27
1 inch	400 psi	4.1	18	0.24
	300 psi	3.8	17	0.23
	200 psi	4.0	20	0.27
	100 psi	5.0	30	0.40
	75 blow	4.4	19	0.25

[a]Durability index = $\frac{P_{age}}{P_{orig}}$.

TABLE 18. ACCELERATED AGING TEST RESULTS FOR AC 40 MIXES.

Aggregate	Compactive effort	Asphalt content % weight	After aging: Penetration P_{age}	After aging: Durability index[a]
3/4 inch	400 psi	3.6	21	0.38
		4.1	21	0.38
		4.6	20	0.36
	300 psi	4.0	15	0.27
		4.5	17	0.30
		5.0	17	0.30
	200 psi	4.8	19	0.34
		5.3	18	0.32
		5.8	25	0.45
	100 psi	5.5	24	0.43
		6.0	19	0.34
		6.5	22	0.39
	75 blow	5.0	21	0.38
		5.5	19	0.34
		6.0	30	0.54
1 inch	400 psi	3.9	17	0.30
	300 psi	4.5	16	0.29
	200 psi	4.3	16	0.29
	100 psi	5.7	22	0.39
	75 blow	4.5	14	0.25

[a]Durability index = $\frac{P_{age}}{P_{orig}}$.

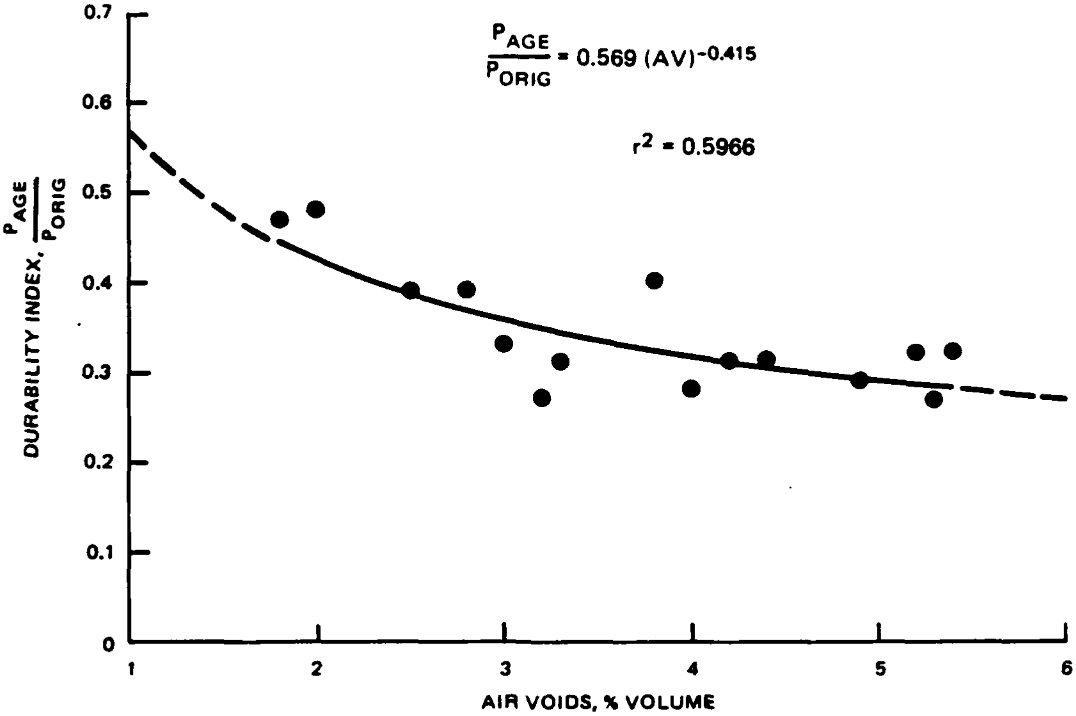

Figure 31. Accelerated Aging Results, 3/4-Inch Aggregate and AC 20 Mixes

indicate good trends for these mixes. Either the penetration test was not sensitive enough to indicate changes in the asphalt because of aging or the extraction and recovery procedures also tended to affect the AC 40.

4. Creep Behavior

Creep tests were among the last tests performed during this study. By this time, trends in previous test data had indicated the 300 psi gyratory compacted mixes were adequately compacted and possessed high strengths. These general observations and a belief that the 400 psi effort was pushing the limits of the gyratory compactor led to the position that a modified laboratory compactive effort with the Model 4C compactor should be limited to 300 psi. The following efforts were selected for use during creep specimen preparation:

Compactive effort	Description
Standard heavy-duty	75-blow per side with a 10-pound manually operated compaction hammer
Modified heavy-duty	300 psi normal pressure, 1-degree gyration angle, for 30 revolutions in the gyratory compactor

The supply of AC 40 asphalt cement was depleted before a full set of mixes was fabricated for testing; this series of tests did not include 3/4-inch aggregate and AC 40 mixes.

Results of unconfined creep testing at laboratory room temperature are given in Table 19. Creep stiffnesses given in the table were computed as simple vertical stress to vertical strain ratios 1 second after step load application. Values of initial creep were computed as the difference in vertical deformation between the first and second 1-second time interval after load application; values shown are in percent per minute. Vertical strains are shown in percent at the end of a 60-minute loading period. If significant vertical strain was noted during testing, tests were halted; vertical strains and testing times, in minutes, were recorded. Only the 200 psi tests were halted because of excessive deformation. Figures 32-39 show deformation-time curves for the mixes tested.

Based on the data, it seemed reasonable to expect that a good indicator of mix creep behavior would be the time needed to reach a constant vertical strain under the most severe load. The amount of time to reach 2 percent vertical strain under the 200 psi load was chosen as the creep behavior indicator. Table 20 summarizes results for this severe loading.

The data infer that high compactive effort on coarse mixes at or slightly lean of optimum asphalt content will produce better creep resistance. Ranking by creep resistance can be accomplished by ordering mixes by decreasing creep times. When this was done for each gradation, mixes compacted by the modified 300 psi compactive effort ranked higher. They are expected to provide better creep resistance under traffic than mixes compacted to standard airfield compactive efforts.

C. SUPPLEMENTAL NONCONVENTIONAL TESTING: CHEMKRETE®-MODIFIED ASPHALT-CEMENT MIXES

This part of the study was intended to examine the effects of a modifier on the behavior of heavy-duty mixes. Chemkrete®, a proprietary asphalt modifier, was added to AC 20 asphalt cement to produce a 4 percent by weight mixture. The modified asphalt was mixed with 3/4-inch limestone aggregate blends to produce a total of about 200 specimens. The Chemkrete® manufacturer recommends a curing period for the modifier to develop its full effectiveness. Half the mixes were not cured; the other half were placed in an oven at 140 °F for a 7-day cure.

Penetration tests were performed on the modified asphalt cement. Penetrations increased 68 percent, from 75 (the unmodified asphalt) to 126 at ambient laboratory temperature (penetration is expressed as 1 unit = 1/10 mm).

Mix designations were abbreviated according to the following format.

Mix	Description of Chemkrete®-Modified AC 20 Mixes
A	4.6 percent by weight -- 400 psi gyratory compaction
B	4.6 percent by weight -- 300 psi gyratory compaction
C	4.9 percent by weight -- 200 psi gyratory compaction
D	5.2 percent by weight -- 75 blow per side hammer effort

TABLE 19. UNCONFINED CREEP DATA SUMMARY.

Mix	Compactive effort	Asphalt content % weight	Creep stress psi	Initial creep stiffness psi	Initial creep % per minute	Final vertical strain[a], %
3/4-inch aggregate and AC 20	300 psi	4.6	200	22,580		3.19 (5)
			100	20,600	5.9	1.54
		5.1	200	26,940	8.7	3.63 (11)
			100	26,390	6.0	1.23
			75	21,680	5.6	1.06
			50	32,950	3.2	0.69
	75 blow	5.2	200	22,960	15.2	4.40 (8)
			100	17,480	8.8	2.01
			75	20,670	8.5	1.60
		5.7	200	23,260	23.5	4.51 (3)
			100	22,710	12.8	3.02
			75	20,680	10.2	2.19
			50	25,710	5.2	1.28
1-inch aggregate and AC 20	300 psi	3.8	200	25,750	8.1	2.00 (4)
			100	17,340	6.1	1.52
			75	18,450	5.7	1.13
			50	17,430	4.7	0.90
	75 blow	4.4	200	26,020	12.1	3.78 (8)
			100	18,460	7.7	1.75
			75	23,110	6.7	1.42
			50	21,880	4.9	1.00
1-inch aggregate and AC 40	300 psi	4.5	200	28,850	6.8	3.45 (16)
			100	23,230	4.8	1.21
			75	23,090	3.3	0.86
			50	18,410	3.8	0.79
	75 blow	4.5	200	21,170	10.3	4.44 (8)
			100	21,960	6.4	1.67
			75	26,460	4.9	1.31
			50	12,930	6.4	1.33

[a]Final strains were measured 60 minutes after load application; when tests were stopped earlier, times are shown in parentheses.

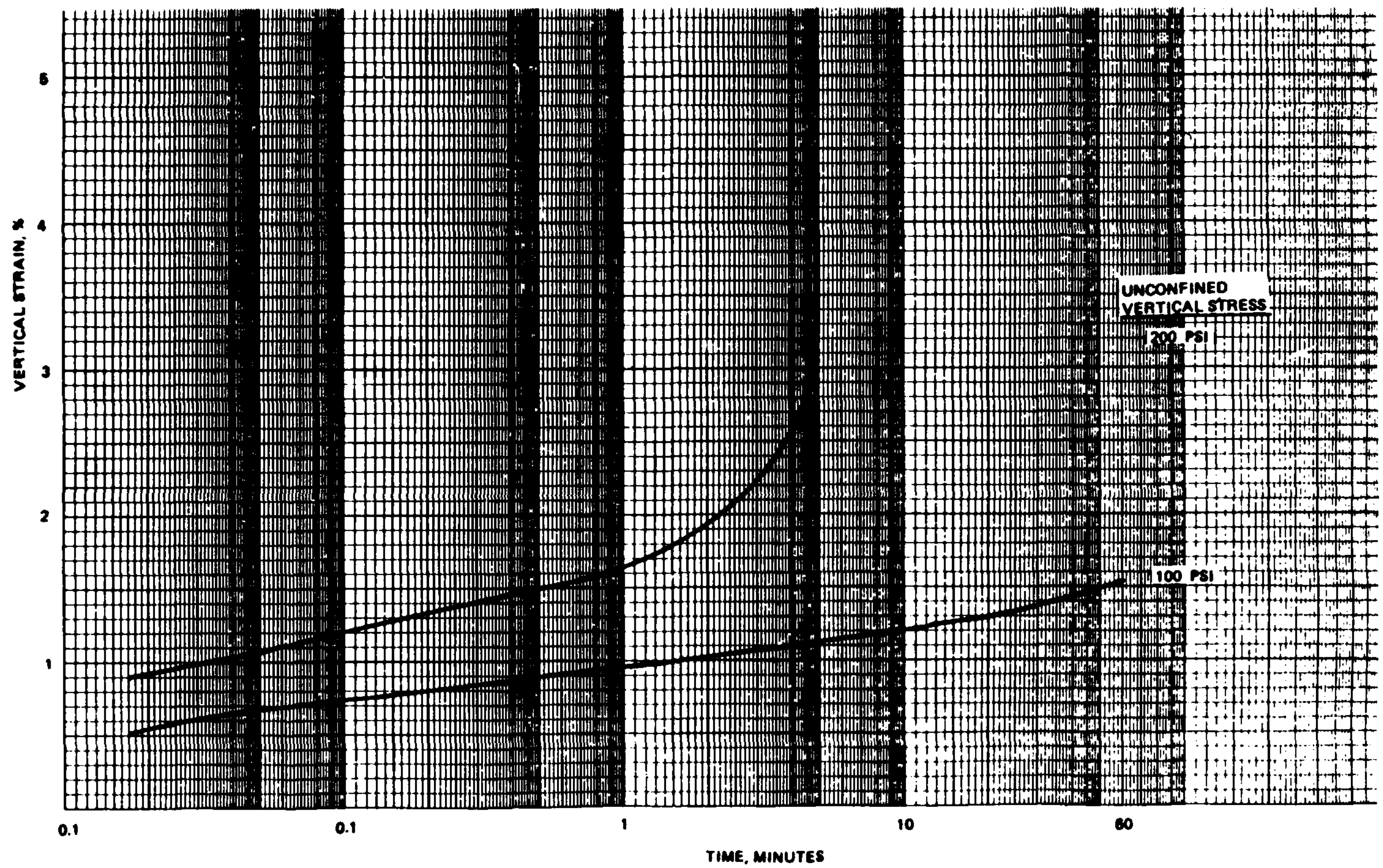

Figure 32. Creep Curves, 77 °F, 3/4-Inch Aggregate, 4.6 Percent AC 20, 300 psi Gyratory Compaction.

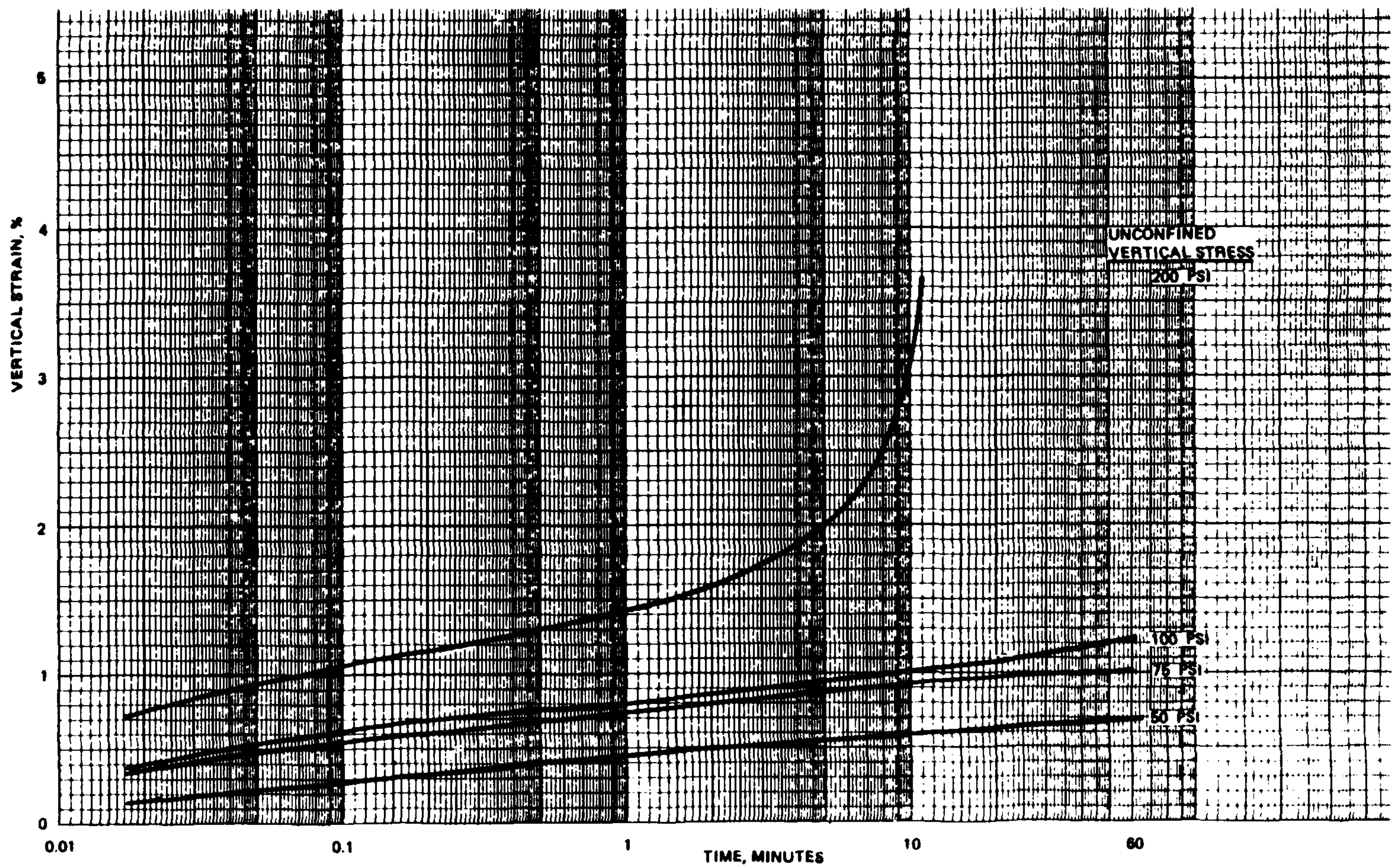

Figure 33. Creep Curves, 77 °F, 3/4-Inch Aggregate, 5.1 Percent AC 20, 300 psi Gyratory Compaction.

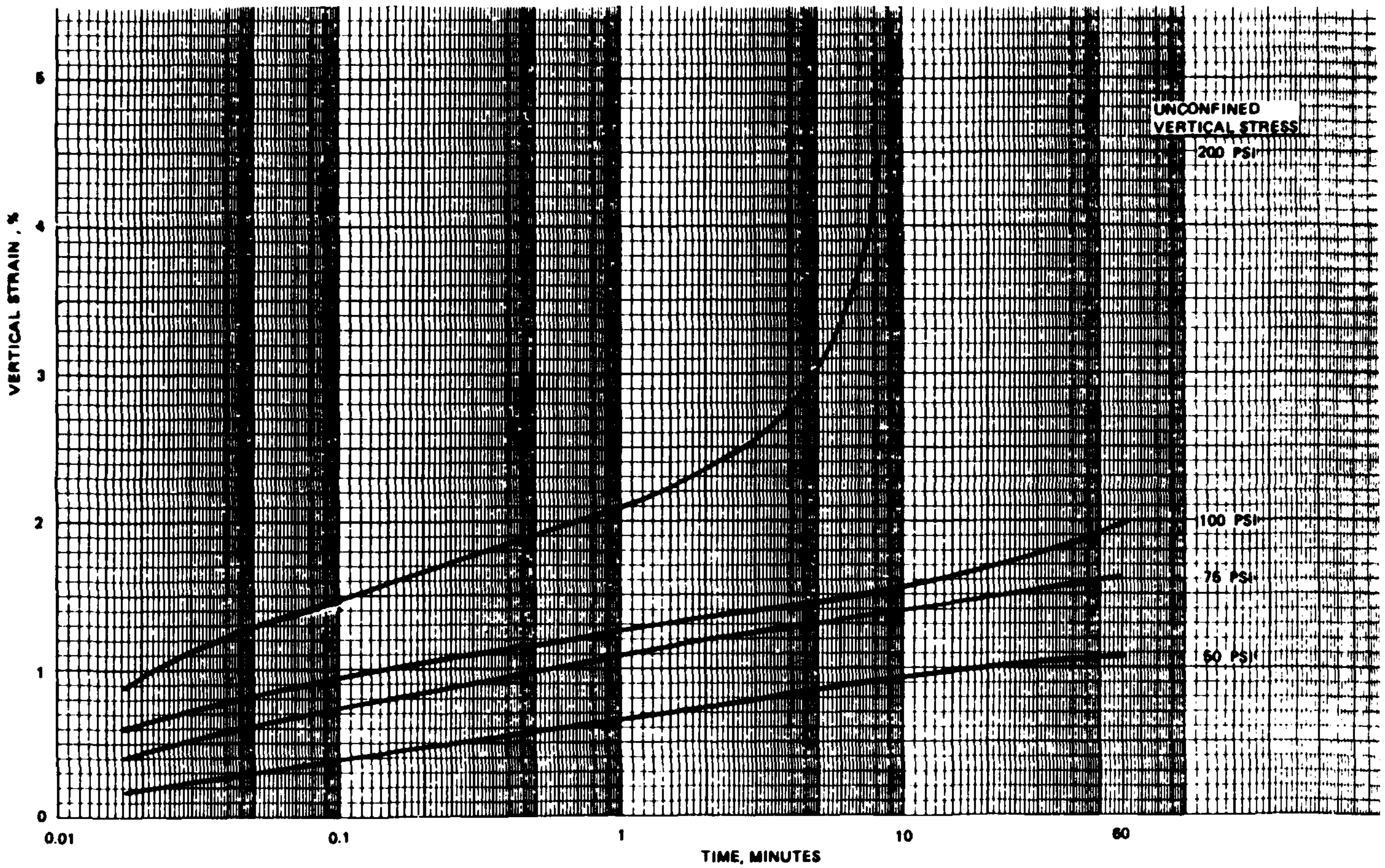

Figure 34. Creep Curves, 77 °F, 3/4-Inch Aggregate, 5.2 Percent AC 20, 75-Blow Hammer Compaction.

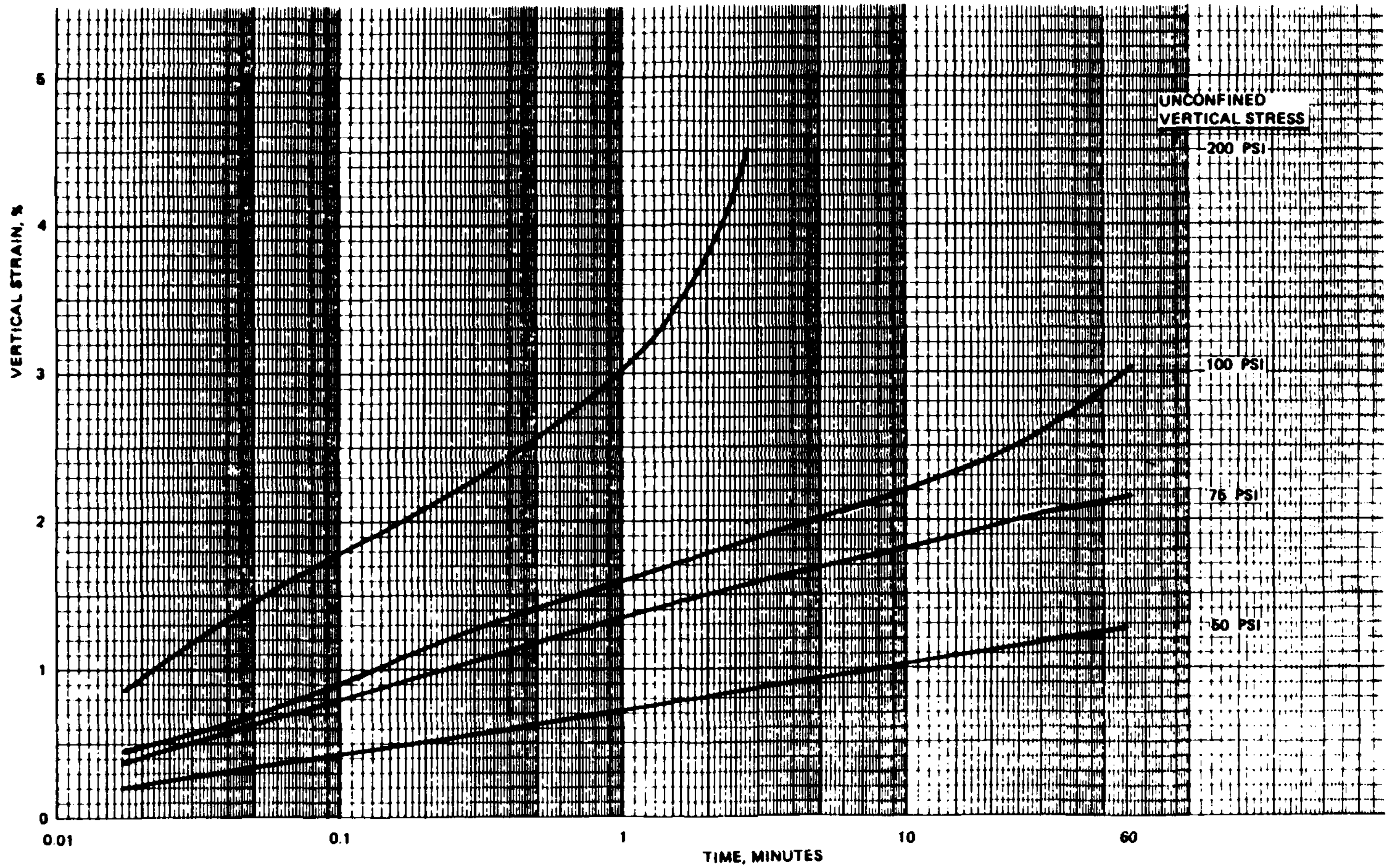

Figure 35. Creep Curves, 77 °F, 3/4-Inch Aggregate, 5.7 Percent AC 20, 75-Blow Hammer Compaction.

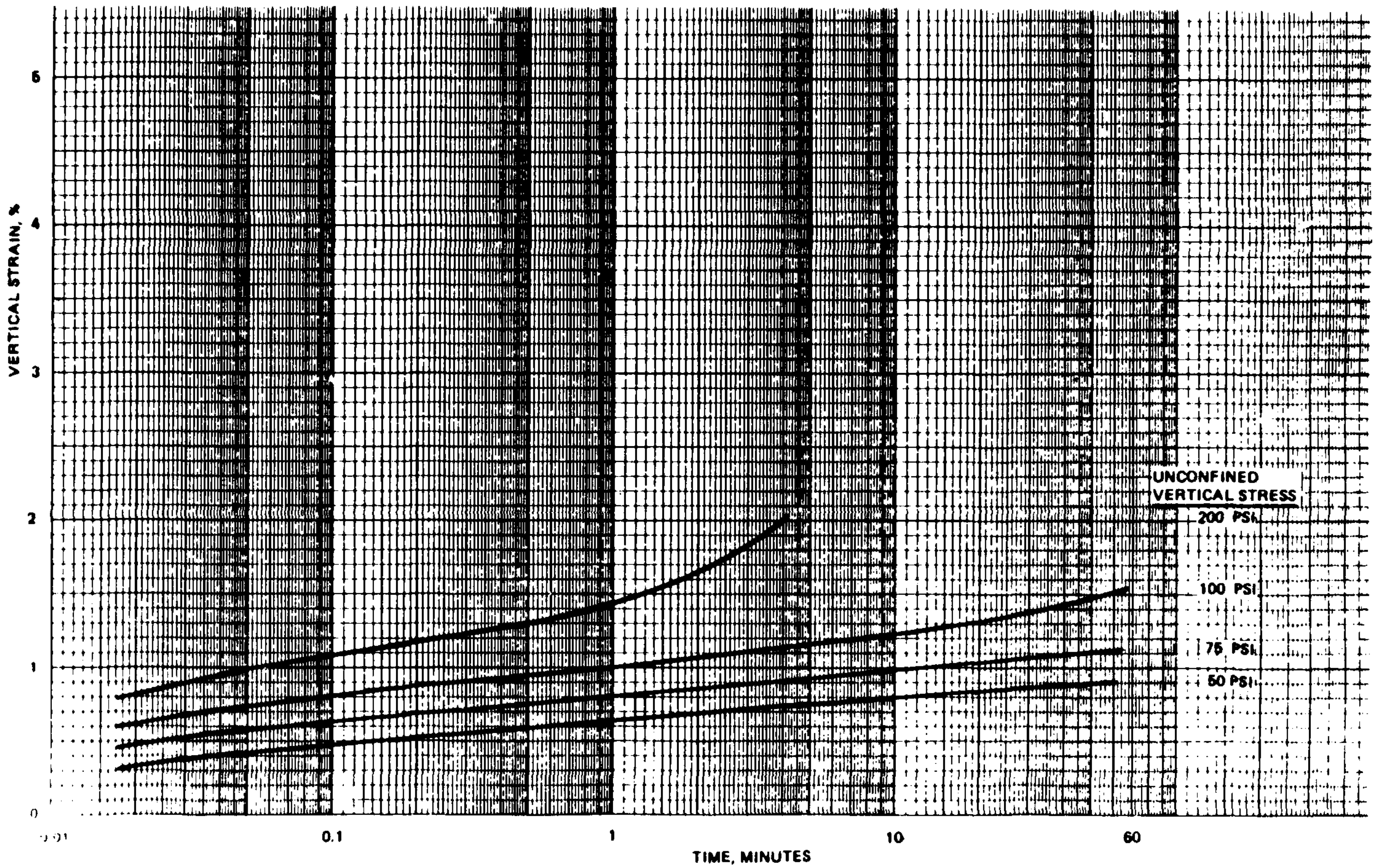

Figure 36. Creep Curves, 77 °F, 1-Inch Aggregate, 3.8 Percent AC 20, 300 psi Gyratory Compaction.

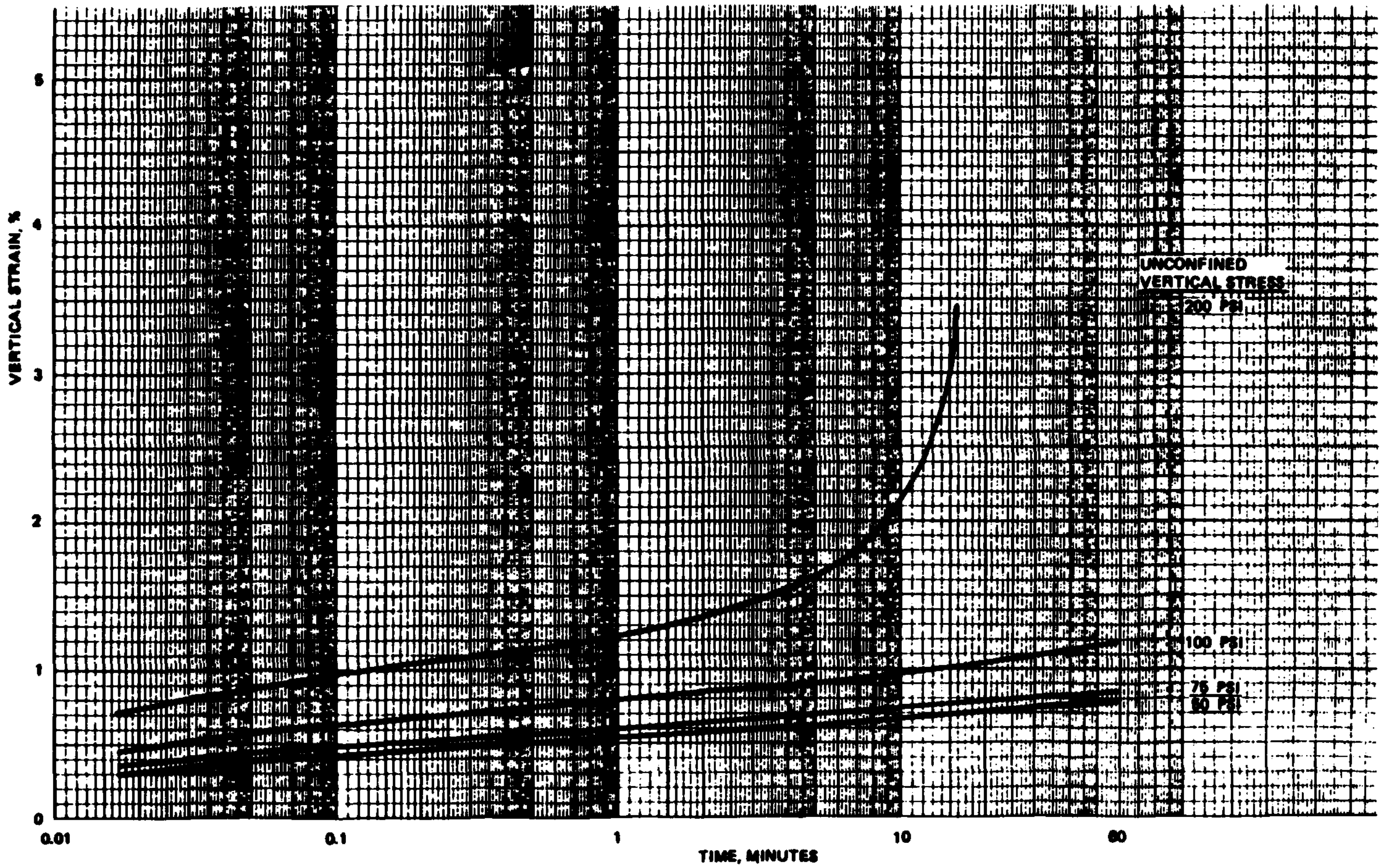

Figure 37. Creep Curves, 77 °F, 1-Inch Aggregate, 4.5 Percent AC 40, 300 psi Gyratory Compaction.

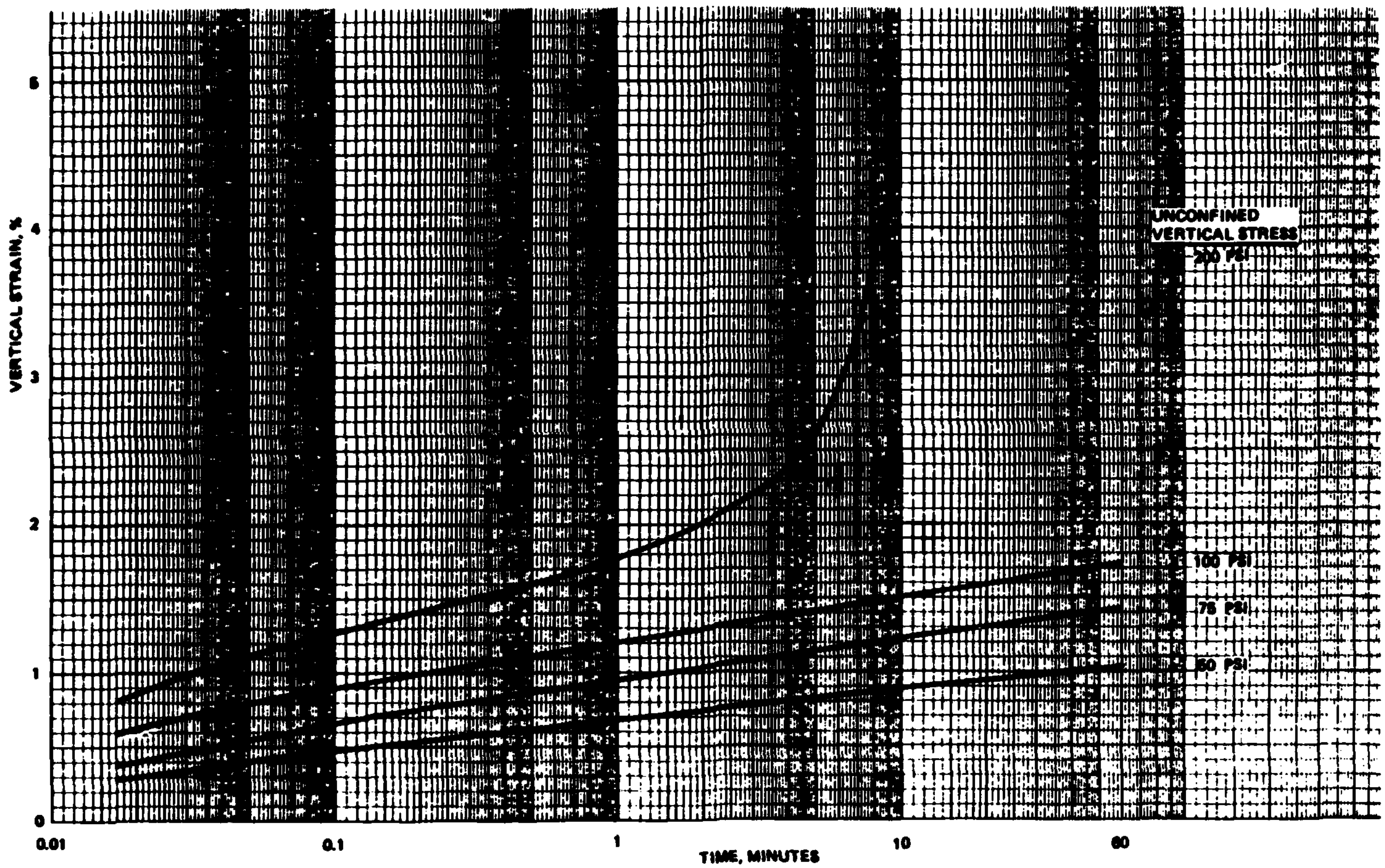

Figure 38. Creep Curves, 77 °F, 1-Inch Aggregate, 4.4 Percent AC 20, 75-Blow Hammer Compaction.

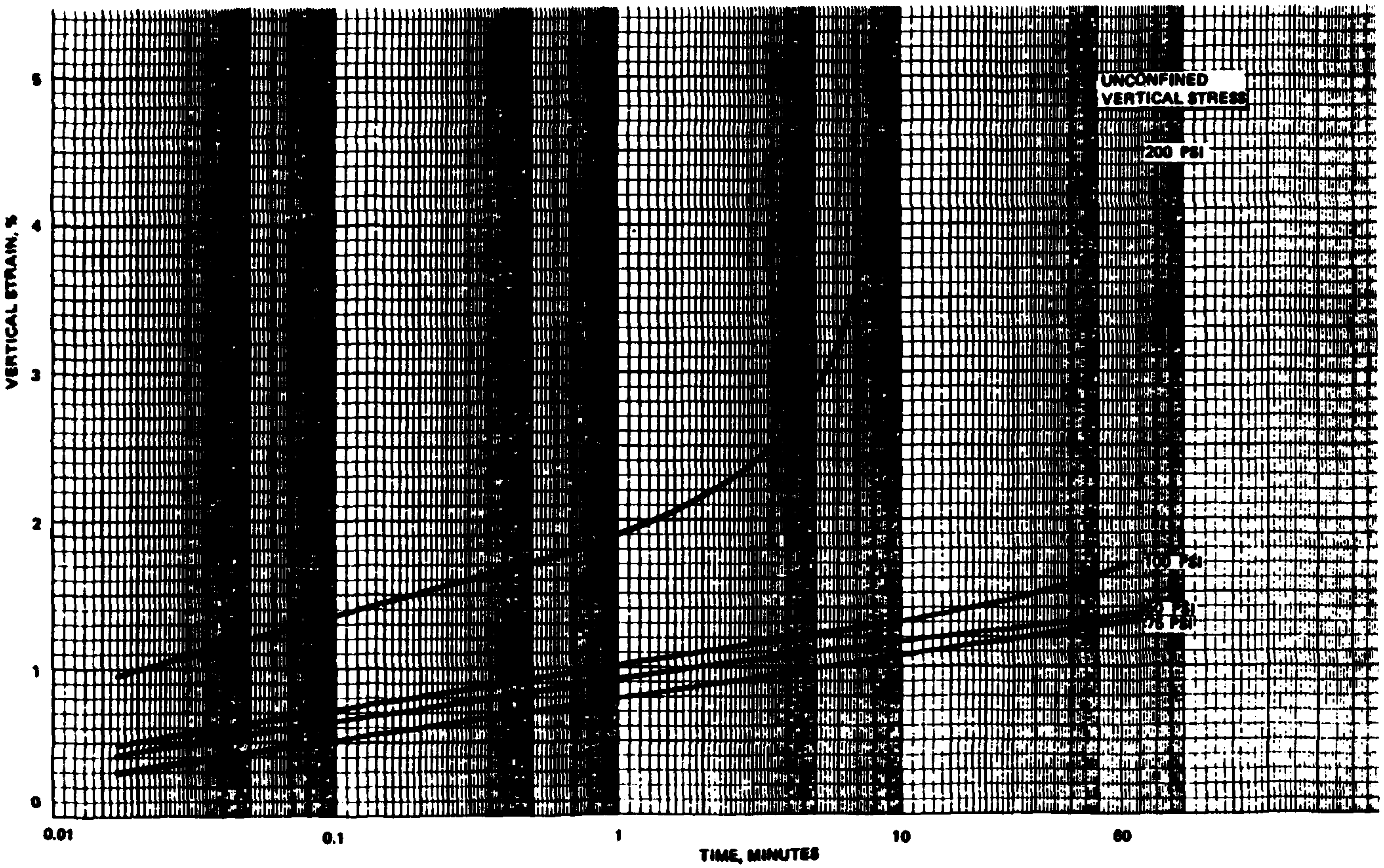

Figure 39. Creep Curves, 77 °F, 1-Inch Aggregate, 4.5 Percent AC 40, 75-Blow Hammer Compaction.

TABLE 20. *UNCONFINED CREEP TIMES AT 200 PSI STRESS.*

Gradation	Compactive effort	Asphalt Type	Asphalt % Weight	Creep time to 2% strain, seconds
1 inch	300 psi	20	3.8	240
	75 blow	20	4.4	126
	300 psi	40	4.5	540
	75 blow	40	4.5	78
3/4 inch	300 psi	20	4.6	132
		20	5.1	300
	75 blow	20	5.2	42
		20	5.7	9.6

Data of Table 21 show that those mixes containing modified AC 20 asphalt generally showed unstable behavior during compaction. The GSIs were above 1.0. At each compactive effort, modified mixes were compacted to denser, more saturated internal structures; this can be seen by comparing total density, voids in the mineral aggregate, and voids filled values from this table with those of Table 11 for unmodified mixes. Obviously, Chemkrete® lowered the resistance of the mix to compaction. However, this also means that a separate mix design has to be performed on modified asphalt mixes; proper design asphalt contents should be lower than unmodified mixes.

1. Resilient Elastic Moduli

Resilient elastic moduli are summarized in Table 22. At 100 °F, loading and unloading moduli (total and instantaneous moduli, respectively) were independent of compactive effort. However, at 77 °F, the unloading response of the 400 psi, gyratory-compacted, uncured mix was higher than other mixes. A general comparison of these data with unmodified mix data showed that modified asphalt mixes had about one-half to two-thirds the resilient modulus of nonmodified mixtures.

2. Direct Shear Data

Direct shear data of Table 23 show that the mixes produced at the highest effort had the highest shear strength. Strengths at the highest effort were about the same as unmodified mixes. As compactive effort decreased and asphalt contents increased, the modified asphalt mixes showed less shear strength than comparable unmodified mixes.

3. Creep Data

Creep data are shown in Table 24. Due to an error in scale factor during these creep tests, the higher vertical stresses used (270 and 150 psi) were not the same as used with unmodified asphalt mixes; creep time responses can not be directly compared with unmodified asphalt mix data in the higher stress ranges. Based on the 75 psi creep responses, the mixes at 300 psi and

TABLE 21. CHEMKRETE®-MODIFIED MIX PROPERTIES[a] AND TEST RESULTS.[b]

Mix	Total density pcf	Voids in mineral aggregate % volume	Air voids % volume	Voids filled %	Gyratory stability index	Cured[c]/ uncured	Marshall stability[b] pounds	Flow[b] 0.01 inch
A	156.2	13.3	2.1	84.2	1.13	U	3,334	14
	156.7	13.1	1.9	85.5	1.24	C	3,657	12
B	154.5	14.3	3.3	76.9	1.20	U	2,964	10
	156.6	13.1	1.9	85.5	1.20	C	3,424	14
C	153.4	15.3	3.6	76.5	1.01	U	2,623	14
	154.5	14.7	2.9	80.3	1.02	C	3,183	15
D	153.4	15.6	3.2	79.5	----	U	2,521	12
	154.5	15.0	2.5	83.3	----	C	2,432	17

[a]Average of groups of 30 specimens (30 cured and 30 uncured).

[b]Average of three tests.

[c]Specimens were cured 7 days in a 140 °F oven before testing.

TABLE 22. RESILIENT MODULI, CHEMKRETE®-MODIFIED MIXES.

Mix	Temperature °F	Cured[a]/Uncured	Average elastic modulus, psi Instantaneous	Total
A	77	U	95,250	69,240
		C	84,000	72,525
	100	U	58,860	43,260
		C	42,300	36,210
B	77	U	78,530	66,120
		C	83,970	72,945
	100	U	52,035	42,075
		C	39,180	34,380
C	77	U	75,960	67,905
		C	80,310	70,695
	100	U	54,075	42,465
		C	35,295	30,210
D	77	U	72,990	63,435
		C	84,105	69,660
	100	U	62,025	46,650
		C	37,815	34,410

[a]Specimens were cured 7 days in a 140 °F oven before testing.

TABLE 23. DIRECT SHEAR DATA SUMMARY (77 °F), CHEMKRETE®-MODIFIED MIXES.

Mix	Cured[a]/Uncured	Normal stress psi	Shear strength psi	Deformation percent diameter
A	U	100	408.9	3.58
		200	556.9	3.60
	C	100	351.1	3.22
		200	533.0	3.92
B	U	100	381.9	3.30
		200	519.7	3.60
	C	100	311.9	5.09
		200	451.9	5.85
C	U	100	329.4	3.69
		200	471.1	4.82
	C	100	363.9	3.85
		200	475.8	4.36
D	U	100	319.3	4.93
		200	407.1	5.36
	C	100	327.8	4.77
		200	425.8	4.28

[a]Specimens were cured 7 days in a 140 °F oven before testing.

TABLE 24. UNCONFINED CREEP DATA SUMMARY (77 °F), CHEMKRETE®-MODIFIED MIXES.

Mix	Creep stress psi	Cured[a]/Uncured	Initial creep stiffness psi	Time to 2 percent vertical strain minutes
A	270	U	21,060	0.25
		C	----	---
	150	U	48,570	16+
		C	19,030	11
	75	U	45,910	60+
		C	20,540	60+
B	270	U	19,410	0.15
		C	18,870	0.07
	150	U	51,780	8+
		C	15,250	2
	75	U	11,550	60+
C	270	U	20,970	0.09
		C	21,172	0.17
	150	U	20,020	2.3
		C	15,100	2.3
	75	U	11,160	60+
		C	12,490	60+
D	270	U	40,150	0.18
		C	20,290	0.07
	150	U	10,580	0.09
		C	20,580	1
	75	U	10,060	30
		C	26,793	60

[a]Specimens were cured 7 days in a 140 °F oven before testing.

75-blow efforts had very similar creep responses: more than 60 minutes to reach 2-percent vertical strain. Cured mixes performed similarly to unmodified asphalt mixes. However, a definite statement cannot be made about the general creep behavior of uncured modified asphalt mixes.

In summary, it appears that modified AC 20 mixes can be compacted to higher densities and will have similar shear strengths, similar creep behavior, and lower elastic moduli than will regular AC 20 mixes, if allowed to cure before traffic.

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

Based on results of this study, a number of conclusions and recommendations were developed. These are based on the use of one type of aggregate, two gradations of the aggregate, three different asphalt types, five compactive efforts, and numerous asphalt contents.

A. CONCLUSIONS

The following conclusions were justified:

- A modified laboratory mix design procedure for surface courses subjected to heavyweight F-15 aircraft traffic is feasible. This study showed that asphalt concrete mixtures, designed using conventional high-contact pressure design criteria and conventional compactive effort, will further densify after construction. The high contact pressures (up to 400 psi) exerted by a heavyweight fighter aircraft were roughly simulated in the laboratory. Test results indicated that instability, leading to rutting, would probably occur in mixes constructed to current heavy-duty compactive efforts.

- Higher compactive efforts than the current 75 blow per side produce stronger surface mixtures. This was found to be valid at asphalt contents lean of standard optimum conditions.

- A satisfactory asphalt concrete mixture can be designed with the gyratory testing machine.

- Mixes made with AC 40 asphalt cement provided greater strength than those made with AC 20 asphalt. To minimize rutting, an AC 40 would be a good choice; however, a stiff asphalt like this may produce significant temperature cracking in areas with wide variations in temperature.

- The 1-inch coarse gradation mixtures performed better under very high compaction pressures (300-400 psi) than did the 3/4-inch graded mixtures. This indicated that, after construction, coarser mixes may not rut as easily from heavy F-15 traffic.

- The use of asphalt cement modifiers, such as Chemkrete®, may assist in the production of mixes with higher construction densities. These types of mixtures may also be more plastic.

B. RECOMMENDATIONS

Based on this study, the following recommendations are made:

- Use a gyratory testing machine to design asphalt mixtures that will be subjected to heavyweight F-15 aircraft traffic. A 300 psi normal pressure should be used to compact specimens in the laboratory.

- Require all aggregates to be crushed. The use of natural sand should not be allowed.

- Use either a 1-inch or a 3/4-inch maximum sized aggregate gradation (see Table 2). Test results indicated that a 1-inch coarse gradation had an advantage in not showing as much unstable behavior during compaction in the gyratory testing machine.

- Select the lowest asphalt content satisfying heavy-duty mix criteria since a high asphalt content is detrimental to good mix performance under very high contact pressures.

- Perform additional work to study other aggregate gradations and other asphalt modifiers. Both natural and man-made asphalts and modifiers need to be evaluated to see if their use could improve mix performance during both hot and cold weather.

1. Recommended Mix Design Methods

Two modified methods of mix design are recommended for asphalt surface courses subject to heavyweight F-15 aircraft traffic. Both methods are based on increased compactive efforts and the heavy-duty mix design criteria. Method I is preferred.

a. Method I: Modified Gyratory Mix Design

The preferred modified method of mix design is based on the use of a gyratory compactor capable of exerting 300 psi normal pressures during specimen preparation. At least three specimens shall be fabricated at each asphalt content across a range of asphalt contents. Steps in the procedure are as follows:

(1) Compact mixes at a 300 psi normal pressure setting and a 1-degree angle of gyration for 30 revolutions of the roller assembly.

(2) Record gyrograph traces of compaction behavior for each specimen. Traces will be used to compute average gyratory stability indices (GSIs) at each asphalt content.

(3) Measure and record average Marshall stabilities and flows.

(4) Compute average weight-volume properties at each asphalt content. Equations from Table 5 can be used.

(5) Select the mix for construction using high-pressure/heavy-duty criteria of Table 6 and average GSI (the ratio of final to intermediate width, from the gyratory trace) values; a GSI of 1.0 shall not be exceeded. Record the following:

- Asphalt content.
- Total mix density.
- Asphalt weight-volume properties.
- Average Marshall stability and flow.

b. Method II: Modified Hand-Hammer Mix Design

When a gyratory compactor is not available, a modified hand-hammer method shall be used to select a mix for construction. This method uses standard 75 blow per side compactive effort and heavy-duty criteria; however, construction density and design asphalt contents are adjusted. Steps in this design procedure are as follows:

(1) Compact mixes using 75 blow per side. At least three specimens per asphalt content shall be compacted over a range of asphalt contents.

(2) Measure and record average Marshall stabilities and flows.

(3) Compute average weight-volume properties at each asphalt content. Equations from Table 5 can be used.

(4) Select the best mix satisfying heavy-duty criteria (Table 6) and note the following:

- Total mix density.
- Asphalt content.
- Average weight-volume properties.
- Average Marshall stability and flow.

(5) Determine modified asphalt content and density of the selected mix as follows:

- Determine modified asphalt content by taking 90 percent of the asphalt content of the second step of (4).

- Compute a modified total density corresponding to the above modified asphalt content. The following equation (modified from Table 5) will be used to select the modified density:

$$\gamma_{mm} = \frac{\gamma_\omega G_s G_B K}{G_s(AC_m) + G_B(1 - AC_m)K}$$

where

γ_{mm} = total modified unit weight of mix

γ_ω = unit weight of water

G_s = apparent specific gravity of aggregate

G_B = specific gravity of asphalt cement

K = Voids filled with asphalt; this value is held constant and must be equivalent to that of the mix selection in the third step of (4) (i.e. 70 percent = 0.70).

AC_m = modified asphalt content = 0.90 x (standard optimum asphalt content by weight (i.e. 4 percent = 0.04)

Figure 40 illustrates use of this modified hand-hammer procedure with 75-percent voids filled with asphalt (K = 0.75).

2. Recommended Mixes for Traffic Testing

The following mixes are recommended for evaluation in the proposed test section at the Engineering and Services Center at Tyndall AFB, Florida.

a. Mix 1: A 1-inch maximum sized aggregate mixture with AC 20 asphalt cement, designed with a gyratory testing machine set to 300 psi pressure (modified design).

b. Mix 2: A 1-inch maximum sized aggregate mixture with AC 20 asphalt cement, designed with the Marshall Method for high-pressure applications (standard design).

c. Mix 3: A 3/4-inch maximum sized aggregate mixture with AC 20 asphalt cement, designed with a gyratory testing machine set to 300 psi pressure (modified design).

d. Mix 4: A 3/4-inch maximum sized aggregate mixture with AC 20 asphalt cement, designed with the Marshall Method for high-pressure applications (standard design).

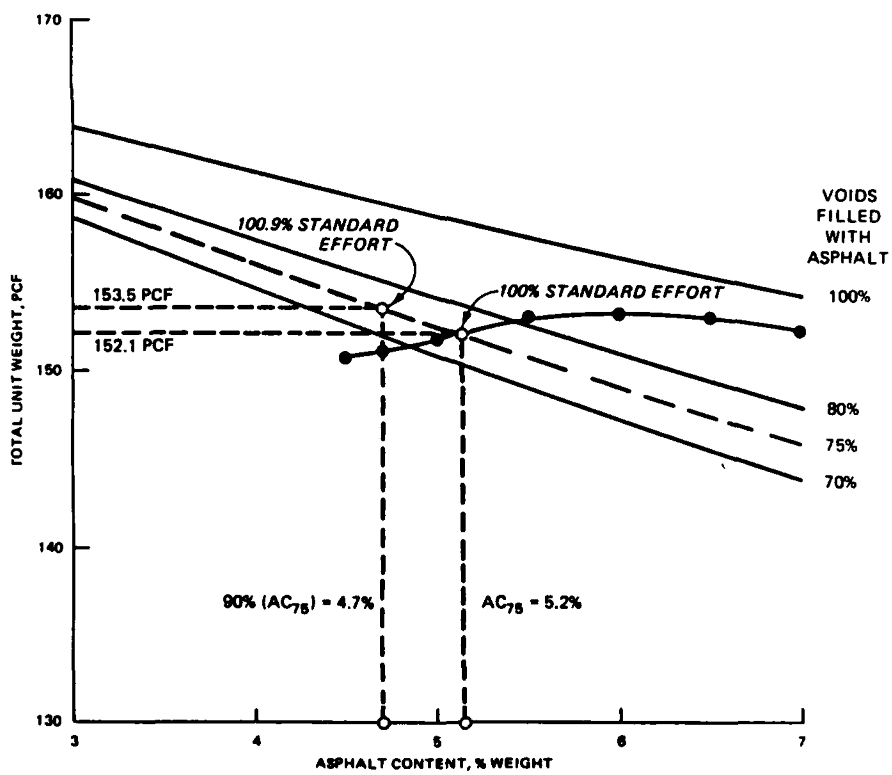

Figure 40. Modified Mix Design Using 75-Blow per Side Hammer Effort.

e. Mix 5: A 3/4-inch maximum sized aggregate with modified AC 20, treated with Chemkrete®, designed with the Marshall Method for high-pressure applications (standard design).

f. Mix 6: A 1-inch maximum sized aggregate with modified AC 20, treated with Chemkrete®, designed with the Marshall Method for high-pressure applications (standard design).

g. Mix 7: A 3/4-inch maximum sized aggregate with AC 40 asphalt cement, designed with the Marshall Method for high-pressure applications (standard design).

h. Mix 8: A 3/4-inch maximum sized aggregate with AC 40 asphalt cement, designed with a gyratory testing machine set to 300 psi pressure (modified design).

i. Mix 9: A 1-inch maximum sized aggregate with AC 40 asphalt cement, designed with the Marshall Method for high-pressure applications (standard design).

j. Mix 10: A 1-inch maximum sized aggregate with AC 40 asphalt cement, designed with a gyratory testing machine set to 300 psi pressure (modified design).

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